ISTANBUL TECHNICAL UNIVERSITY ★ ENERGY INSTITUTE

INVESTIGATING THE EFFECT OF THERMAL BRIDGES THROUGH BALCONIES IN RESPECT OF OVERALL BUILDING ENERGY PERFORMANCE

M.Sc. THESIS

Zafer YÜCE

Energy Science and Technology Division

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Thesis Advisor: Assoc. Prof. Dr. Hatice SÖZER

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ ENERJİ ENSTİTÜSÜ

BALKONLARDA OLUŞAN ISI KÖPRÜLERİNİN BİNA ENERJİ PERFORMANSINA OLAN ETKİLERİNİN İNCELENMESİ

YÜKSEK LİSANS TEZİ

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Enerji Bilim ve Teknoloji Anabilim Dalı

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Zafer YÜCE, a M.Sc student of ITU Institute of Energy student ID 301131031, successfully defended the thesis entitled "INVESTIGATING THE EFFECT OF THERMAL BRIDGES THROUGH BALCONIES IN RESPECT OF OVERALL BUILDING ENERGY PERFORMANCE", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 14 December 2015
Date of Defense : 22 December 2015

To my family,

FOREWORD

Special thanks to my advisor Assoc. Prof. Dr. Hatice SÖZER for her precious time and support.

November 2015

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ABBREVIATIONS

ASHRAE : American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASIEPI : Assessment and Improvment of the Energy Performance of Building Directive Impact.

BREEAM : Building Research Establishment Environmental Assessment Methodology.

EN : European norm.

EPS : Expanded polystrene.

HVAC : Heating, ventilation and air-conditioning.

LEED : Leadhership in Energy and Environmental Design.

OECD : Organisation for Economic Co-operation and Development.

SI : System international.

TOE : Ton oil equivalent.

XPS : Extruded polystrene.

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INVESTIGATION THE EFFECTS OF BALCONY THERMAL BRIDGES ON BUILDING ENERGY PERFORMANCE

SUMMARY

Depletion of fossil fuels, increasing energy prices and carbon emissions are high-lightened need for energy efficiency. Recently, countries develop their own energy codes and standards day by day. Green energy technologies, sustainable solutions and energy efficiency are preferred. Public policies and voluntary agreements are for people to consume low energy. With regard to their operation times, buildings account a considerable amount of energy consumption.

In Turkey, most of buildings consume more energy than European countries. Lack of insulation on building envelope leads to an increasing pattern in energy consumptions as well as inaccurate commissioning process and imprecise life cycle cost assessments among many other related aspects.

Thermal bridge issues generally not considered during design, construction and retrofitting phases. However, thermal bridges accounts significant role on overall energy consumption in building. Thermal bridges could occur different part of buildings such as roof, internal floor, pillar, ground floor and balcony. Through a building's life cycle thermal bridges effect energy consumption, durability and indoor environmental quality of building. Unwanted heat transfer leads to increase in energy consumption. Thermal bridge surfaces have lower temperature than indoor ambient temperatures. This situation may causes condensation in surface or in wall. Thus, durability of construction decreases. Furthermore, condensation on indoor surfaces effects moisture level and fungi grow in indoor spaces. Undesired indoor air quality may lead to decrease in comfort, worker performance. Moreover indoor air directly effects the health.

In this study, balcony thermal bridges are investigated in terms of energy consumption also, surface condensation potential is assessed on the basis of surface temperature factor calculation. In order to conduct a thermal bridge study, an uninsulated two story residential building is selected where is located in Manisa Province. Base on building data, two dimensional heat transfer simulations are performed with Therm software. Therm outputs are derived to overall U value and these values are inputted into the eQuest software. Effects of thermal bridges are examined through a building energy model.

Three case studies are developed as following;

- Case -1 : Existing condition (uninsulated),
- Case -2 :Exterior wall insulated condition,
- Case -3 : Exterior wall and balcony slab insulated condition.

With the application of insulation layer to exterior wall (Case-2), heating energy consumption decreased by 48.8% also, cooling energy decreased by 22.3% compared to the existing case. With the insulation of exterior wall and balcony slab (Case-3), heating energy consumption decreased by 4.4% and cooling energy consumption decreased by 0.8% compared to case-2.

BALKONLARDA OLUŞAN ISI KÖPRÜLERİNİN BİNA ENERJİ PERFORMANSINA OLAN ETKİLERİNİN İNCELENMESİ

ÖZET

Fosil yakıtların azalması, artan enerji fiyatları ve fosil yakıtların çevreye olan olumsuz etkileri ile birlikte sürdürülebilirlik, enerji verimliliği karbon ayak izi gibi terimler günümüzde popüler bir hale geldi. Bir çok farklı disiplinin araştırmacıları artık bir araya gelerek enerjinin nasıl daha verimli kullanılabileceği hakkında çalışmalar yapmaya başladılar. Gelişmiş ülkeler enerji kullanımında yasal sınırlandırmalar getirerek insanları enerji verimli çözümler kullanmaya teşvik etmektedirler. Bunun yanında yenilenebilir enerji kullanımına teşvik sağlayarak yenilenebilir enerji üretiminin artması ile karbon salınımlarını ciddi orandan düşürmekle birlikte sürdürülebilir bir çevre oluşturmaktadırlar.

Sürdürülebilir yaklaşım binanın ilk tasarım aşamasından itibaren dikkate alındığında aslında faydalanılabilecek bir çok kaynak olduğu görülebilmektedir. Bina tasarımının bu kaynakların kullanımına uygun yapılması ile binanın enerji tüketim miktarı büyük ölçüde azaltılabilmektedir. Bu şekilde doğal kaynaklarımızı daha etkin kullanmakla birlikte çevre ile dost sürdürülebilir şehirler inşa etmiş olmaktayız. Güneş enerjisi açısından baktığımızda günümüzde binanın ısıtma ve soğutma ihtiyacı belirli bir ölçüde sağlanabilmektedir. Eski mimarileri incelediğimizde Nevşehir bölgesinde bulunan tarihi yapılarda bunların çok eski örneklerine de rastlamak mümkün. Isı kütlesi denilen bu sistem ısı enerjisini içinde depolayarak ihtiyaç olan saatlerde çevresine yaymaktadır. Bölgedeki hakim rüzgar yönüne göre yapılan tasarımlarda havalandırma ihtiyacı da bir ölçüde karşılanabilmektedir. Binaların en çok enerji tüketen sistemlerinin ısıtma, soğutma ve havalandırma olduğu düşünüldüğünde yapılan tasarrufun da önemi kavranabilecektir.

Diğer bir yandan fosil yakıtların ömrünün sonuna geldiğini düşünürsek enerjimizi daha verimli kullanmak, alternatif enerjilere yönelmek ve sürdürülebilirlik kavramını projelerde bütünsel bir şekilde kavramak gerektiği sonucunu çıkartabiliriz.

Enerji genel olarak ulaşım, sanayi ve konutlarda tüketilmektedir. Binaların aydınlatma, ısıtma ve soğutma, sıcak su ihtiyacı gibi kullanımlar düşünüldüğünde ve binaların günlük kullanım süreleri de göz önüne alındığında tükettikleri enerjinin bir hayli fazla olduğu görülmektedir. Ülkemizde konut sektöründeki canlılık da düşünüldüğünde Türkiye için binalarda enerji verimliliği bir zorunluluk haline gelmiştir denilebilir. Enerjide dışa bağımlı oluşumuz ve mevcut yapıların enerji verimsiz oluşu bizi enerji verimliliği konusunda alt sıralara taşımaktadır. Almanya, İngiltere, Amerika gibi gelişmiş ülkeler LEED, BREEAM, Passive House gibi bina etiketleme prosedürleri geliştirerek binaların enerji tüketimlerini azaltıp enerji verimli teknolojilerin yaygınlaşmasını sağmaktadırlar.

OECD ülkelerinde evsel binalarda enerji tüketiminin toplam enerji tüketiminde payının %43 olacağı öngörülmektedir. Türkiye'de ise toplam enerjinin %32'si binalarda, %33'ü ise ısıtma enerjisi için harcanmıştır. Veriler Türkiye'nin2004'te 19.9 MTEP, 2014'te 43.7 MTEP enerji tükettiğini göstermektedir. 10 yıl içinde toplam tüketimin %100'den fazla arttığı görülmektedir. Binaların toplam enerjinin yaklaşık 1/3'ünü tükettiği yukarıda açıklanmıştı. 2013 yılından alınan verilere göre Türkiye elektrik enerjisinin enerjisinin %43.8'ini doğal gazdan üretmektedir. Tüketilen doğal gazın % 30.8'i ve elektriğin %49'u binalarda kullanılmıştır.

Enerji verimliliği strateji belgesine göre Türkiye 2023 yılında gayrisafi yurtiçi hasıla başına tüketilen enerji miktarını 2011 değerine göre %20 azaltmayı hedeflemektedir. Enerjinin verimli kullanılması bu hedefin gerçekleştirilmesindeki en önemli kriterdir.

Binalarda net ısıtma enerjisi ihtiyaçlarını hesaplama kurallarına ve binalarda izin verilebilir en yüksek ısıtma enerjisi değerlerinin belirlenmesine dair Türk Standardı TS 825 ilk olarak Bayındırlık ve İskan Bakanlığı tarafından 1999 yılında resmi gazetede mecburi standart tebliği olarak yayınlanmıştır. Bu standart için zorunlu uygulama ise 2000 yılında başlamıştır. Bu standart, derece gün sayılarına göre Türkiye'yi farklı bölgelere ayırmıştır. Binaların senelik ısı ihtiyacı yüzey/hacim oranı esas alınarak faklı bölgeler için belirlenmiştir. Günümüzde denetimin yeterli yapılmamasına bağlı olarak ısı yalıtım çalışması yapılmayan binalar hala bulunmaktadır. Bunun yanında işletmeye alma prosedürlerinin tam anlamıyla uygulanmıyor oluşu binalarda enerji kayıplarını büyük ölçüde arttırarak tüketim oranlarımızı Avrupa ülkelerine göre kıyasla yükseltmektedir.

Isı köprüleri, binalarda malzeme geçişlerinde ve/veya kalınlık değişimlerine bağlı olarak ısıl iletkenliğin değişmesi nedeniyle ısı geçişinin artmasıdır. Artan ısı geçişi enerji tüketimini arttırmakta ve binada hasara neden olabilmektedir. Isı köprülerinin oluştuğu yüzeylerde kış aylarında yoğuşma sıcaklığına inilmesi ile birlikte yoğuşma olayı gerçekleşmektedir. Yoğuşma, iç ortamda maddi kayıp yaratacağı gibi içerideki nem oranını etkilemesi ve küf oluşumunu tetiklemesi gibi nedenlerden ötürü iç hava kalitesini ve ısıl konforu olumsuz olarak etkilemektedir. İç hava kalitesindeki bu kötüleşme beraberinde hasta bina sendromu denilen durumunu oluşturmakta ve bina sakinlerin hastalanmasına neden olabilmektedir. Bu tür durumların iş yeri ve okullarda görülmesi performansın insanların performansının düşmesine beraberinde maddi kayıplara neden olmaktadır. Diğer bir yandan yüzeyde yoğuşma olması bina mukavemetini olumsuz etkilemektedir.

Isı köprüleri binalarda çatı, balkon, köşeler, ara katlar, iç duvarlar, toprak temaslı zeminler, kolon ve sütunlar, pencere ve kapılarda meydana gelebilmektedir.

EN 14683 standardında binalarda oluşabilecek değişik ısı köprüleri için kapsamlı bir tablo oluşturulmuştur. Bu tablolardan üzerinde çalışılacak ısı köprüsü seçilerek tabloda verilen lineer ısıl iletkenlik değerinin okunması ile birlikte dış duvarın ısıl iletkenliğinin ısı köprüleri ile nasıl değiştiği hesaplanabilmektedir. Elde edilen ısıl iletkenlik değeri ile birlikte binanın toplamda kaybedeceği ısı miktarı hesaplanıp, ısı köprüsünden kaynaklanan enerji kaybı bulunabilmektedir. Fakat EN 14683 standardı kullanılarak yapılan hesaplarda lineer ısıl iletkenlik değeri tablolardan okunduğu için içinde bir miktar hata pay da barındırmaktadır.

EN 10211 standardı ısı köprülerinin nümerik olarak haşlanmasını açıklamaktadır. Bu standartta hesaplanmak istenen geometri standartta tanımlandığı sınır koşullar sağlanmak üzere spesifik bir bölgenin lineer ısıl iletkenliği hesaplanabilmektedir. Sonlu elemanlar yöntemi ile çalışan programlarda hesaplanmak istendiğinde standardın sonunda bulunan testlerin kullanılacak programa yaptırılması ve çıkan sonuçların standartta verilen sonuçlarla ne ölçüde uyduğu mukayese edilmelidir.

Bu çalışmada Manisa'da iki katlı bir evsel bina seçilerek üç tane vaka çalışması yapılmıştır. Yapılan hesaplamalar EN 10211 standardı çerçevesinde yürütülmüş olup balkon kesiti için ısı köprü çalışması yapılmış ve bina enerji performansına olan etkileri incelenmiştir. Hesaplamalar sonucunda balkonlarda oluşan ısı köprülerinin ısıtma enerjisi tüketiminde %4.6, bina enerji performansına %3.1 mertebesinde etkisinin olduğu görülmüştür.

1. INTRODUCTION

Energy efficiency, sustainibility and low emmission terms become more popular between various disciplines recently. Negative effects of fossil fuels to the environment, their increasing prices and depletion lead to investigate new energy technologies and energy efficiency.

With the civilization of world, people spend most of their time in buildings. Regarding operation times of buildings, their energy consumption accounts a considerable amount money. Estimated residential energy consumption in Organisation for Economic, Co-operation and Development (OECD) Countries is 43% and in non-OECD counties this value increases 57% for 2015 [1].With respect to energy consumption in buildings, developed countries enhanced different energy efficiency concepts such as United States developed Leathership in Energy and Environmental Design (LEED), Germany developed Passive House and United Kingdom developed Building Research Establishment Environmental Assessment Methodology (BREEAM) in order to decrease carbon emissions of buildings.

In 2004, Turkey's consumption recorded as 19.9 million Ton Oil Equivalent (MTOE). This value increased up to 43.7 MTOE by 2014 [2]. In Turkey, buildings account 32% of total energy [3]. Besides, 33% of total energy consumed for heating needs. Because of energy dependecy of Turkey to the other countries, energy efficiency is more important than other countries for Turkey.

Heat gain and loss of building can play an important role addressing the issue of energy efficiency, besides, thermal bridge is an important aspect of heat transfer. In general, effects of thermal bridges are not considered during design, construction and retrofitting phases. However due to buildings high heating energy consumption effects of thermal bridges need to considered. Not only the energy efficiency issues but also effects on indoor environmental quality highlights importance of thermal bridge. Recent developments in energy efficiency gave birth the need for investigation of thermal bridges in order to achieve low carbon emission buildings

[4]. In Turkey, TS 825 standard which accounts thermal insulation requirements for buildings was published in 1999 [5]. However, insulation studies have not completed for all buildings [6].

In Turkey, energy consumption per square meter is higher than European countries because lack of insulation studies [6]. Furthermore, ineadequacy of commissioning process increases energy consumption in a significant way.

This study assesses the significance of thermal bridge that occurs on building envelope, specifically on balconies. In order to conduct this exploratory study, a two story building located in Manisa, Soma was employed for simulations.

Chapter two begins by explanation of literature, it will then go on to standards related to thermal bridge.

Chpater three concerned with methodology used for this study.

Chapter four gives a detailed overview of case study which explained briefly in summary section including calculations and results of simulation.

Chapter five presents results of analysis and simulation also their comperative results of each cases.

2. LITERATURE REVIEW

Up to now, a number of studies have investigated the effects of thermal bridges on building energy performance as mentioned below;

In Assessment and Improvement of the Energy Performance of Building Directive Impact (ASIEPI) project Erhorn H. et. al. studied effects of thermal bridges on building energy performance. The study asserts that, the effect of thermal bridge on heating energy demand may raise up to 30%. Nonetheless, it has less impact on cooling energy demand [7].

ASHARE inspected 40 common mid-rise and high-rise building construction in order to provide thermal performance data. The study showed that, 3D thermal bridges have a great impact on assembly effective R-value [8].

Yılmaz D., investigated six story tunnel at a social housing unit in Ankara by consideration of six common thermal bridge areas as; balcony, basement wall, roof, floor slab, internal partition and corner detail on the basis of Passive Hose Principles. The study suggests that, heat loses through thermal bridges are highest in balcony. Moreover, insulation of balcony floor slab both above and below may reduce thermal bridge heat losses by 32%, also usage of thermal break element for balcony can reduce the thermal bridge heat losses by 84%, additionally floor surface temperature may increase and mold growth can be prevented [9].

Ge et al. examined multi-unit residential buildings with regard to thermal bridge effect of balcony slab on overall U-value of building envelope, space heating energy and space cooling energy consumption. Moreover, in the research, balcony thermal break was considered on the basis of typical winter design conditions for Toronto. The study showed that U-value of balcony slab can be improved by 72-85% and minimum floor surface temperature is increased from 6.1 °C to 12.5°C, besides, space heating energy consumption can be decreased by 5-13% and space cooling energy is reduced less than 1% with the introduction of balcony thermal brake due to simulation results [10].

Theodosiou and Papadopulous, investigated the thermal bridge on a typical three-story apartment building with an open ground floor space (piloits) and a flat roof based on Thessaloniki climate conditions. According to the study, annual heating load of building may be reduced by 30%, on the other hand, thermal bridge effect on annual cooling load is negligible [11].

Evola et al. studied the effects of thermal bridges for terraced houses and semi-detached houses regarding Italian climate conditions. As a first step, thermal bridge effect on heating and cooling load was analyzed then correction of thermal bridges in terms of financial based on discounted payback period were calculated. The results indicates that, heating energy consumption can be decreased by 25% for terraced houses and 17.5% for semi-detached houses. However, cooling energy consumption of the building may be decreased by 8.5% with the correction of thermal bridges. Financial analysis showed that, correction of thermal bridges is not cost-effective in Italian climate [12].

Ge and Baba evaluated dynamic effect of thermal bridges on energy performance of a low rise residential building depends on cold and hot climatic conditions. The impact of direct 2D/3D modelling method, equivalent U-value method and equivalent wall method are identified. For the cold climate simulation results suggest that, thermal bridges increase annual heating load by 18%, besides, using 3D dynamic method, annual heating load was calculated 13% higher than using equivalent U-value method and 9% higher than equivalent wall method. On the other hand, for the hot climate, simulation results indicate that, thermal bridges increase annual cooling load by 20%. Moreover, using 3D dynamic method, annual cooling load is calculated 17% higher than the equivalent U-value method, also, 14% higher than equivalent wall method [13].

Gomes et al. employed combined thermal properties method in order to investigate impact of thermal bridges on thermal performance of light steel framing buildings in Brazil. In the study, two air-conditioned commercial buildings were used. As regards to simulation results, inclusion of metal frames in simulation increases thermal peak load by 10%, also, annual energy consumption increases 5% [14].

Ibrahim et al. investigated windows offset thermal bridge from exterior walls of a typical French house. According to the study, percentage of the windows' offset thermal bridge can effect building energy load approximately 4-8% [15].

Guolity et al. inspected thermal performance reinforced polymer thermal brakes for balconies or roof projections for a typical residential building in Switzerland. The study suggest that, correction of thermal bridges may decrease heating demand by 41% [16].

Cappeletti et al. studied the effects of window frame thermal bridges in terms of linear thermal transmittance on the basis of EN 10211:2007. The frame position and the configuration of the window hole insulation are investigated. According to the study, the position of the frame and moving window internal to external position decreased linear thermal transmittance by 70-75% [17].

Sezer and Yeşilyurt carried out an investigation into the effects of insulation on linear thermal transmittance and heat loss. Building's envelopes are analyzed in a residential district selected for the study in Bursa province, Turkey. The study claims that, linear thermal transmittance of uninsulated internal floor slab is nearly 35% greater than externally insulated internal floor slab. Moreover, linear thermal transmittance of uninsulated internal floor slab is 23% higher than above and below insulated internal floor slab [18].

Collectively, Publicly reported studies on thermal bridge outline a critical role of this subject. In the light of these studies we have investigated our building. This dissertation studies a residential building to investigate the effect of balcony thermal bridges on building energy performance.

2.1 Standards related to thermal bridges

European and Turkish standards which covers thermal bridge issues are mentioned below;

The European Standard EN 10211 provides numerical calculations for a three-dimensional and two-dimensional geometrical model of a thermal bridge in order to determine heat flows to assess heat loss of building or a specific part of it and minimum surface temperatures to investigate overall heat loss and surface condensation risk. The calculations are built upon following two assumptions [19]:

- All physical properties are independent of temperature,
- There are no heat sources within the building element.

Derivation of linear and point thermal bridges and surface temperature factors can be derived using EN 10211 as well.

The European Standard EN ISO 14683 presents a time-effective approach to determine heat flows through linear thermal bridges based on thermal bridge atlases where values of linear thermal transmittances are reported. This standard determines manual calculation methods for thermal bridges.

Calculation of thermal bridges in terms of numerical or thermal bridge atlases affect accuracy range of results. The numerical calculations have ±5% and catalogues have ±20% accuracy range [20].

The European Standard EN 6946:2007 identifies calculation methods of the thermal transmittance and thermal resistance of building elements excluding doors, windows and other glazed elements. Calculation of thermal transmittance is based on thermal resistance of building elements [21].

Finally, Turkish Standard TS 825 proposes the rules calculating net heating energy and determination of maximum permissible heating energy value in the buildings. However, this standard does not provides a certain calculation methods of thermal bridges for different building sections. According to TS 825, thermal bridges must be calculated considering EN 10211 and EN 14683 or EN 6946 [22].

Table 2.1 : Standards related to thermal bridge.

Name of the standard	Effectiveness of the standard	Scope of the standard	Calculation methods based on
EN 10211	European standard	Numeric calculation of thermal bridges	
EN 14683	European standard	Calculation of thermal bridges based on catalogue	EN 10211
EN 6946	European standard	Calculation of linear thermal transmittance	
TS 825	Turkish standard	Calculation of insulation thickness	EN 10211, EN 14683, EN 6946

3. METHODOLOGY

Fast grow in construction sector in Turkey increased the attention for building energy performance. As mentioned in previous chapters heating and cooling requirement accounts a considerable amount of energy consumption in Buildings also in country level as well.

Following flow chart illustrates main steps of the methodology used in this study

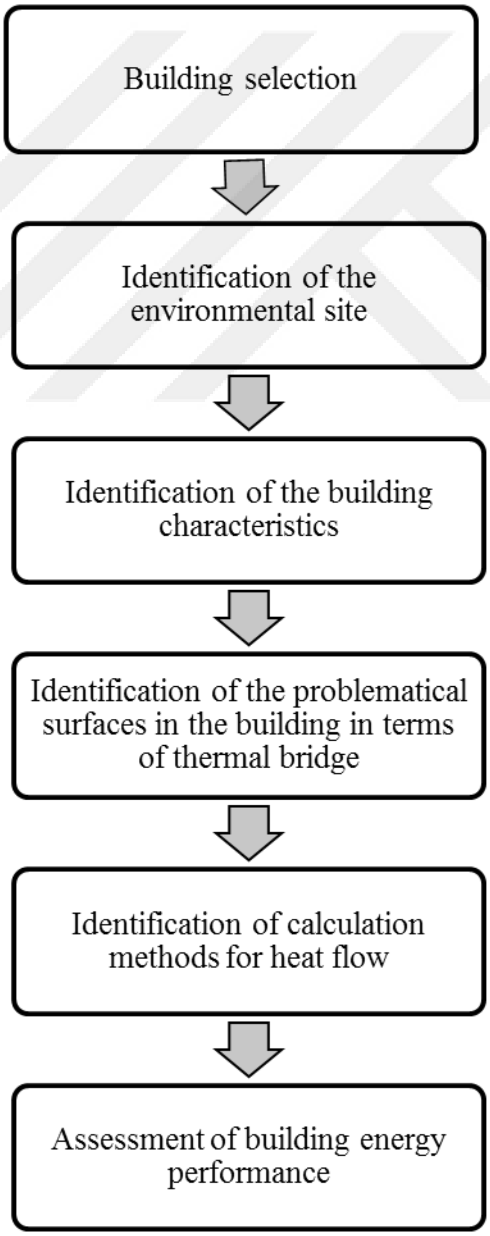


Figure 3.1 : Methodology of this study.

In order to evaluate thermal bridge effects on building energy performance for residential buildings, a typical single block concrete two story building which located in Manisa province is selected. Later, environmental site of the building is identified based on stastistical data depending on annual hourly weather data including minimum, maximum and average temperatures, solar radiation values and precipation profiles to evaluate heat loss through envelope to outside space. Then, building characteristics are identified in terms of building footprint, envelope details including material properties, layers of walls, shape of windows and doors, type of roof, heating and cooling systems of building. By the identification of environmental site, next step was, identification of problematical surfaces on building envelope with regard to thermal bridge. In my study, especially balcony slab is investigated. Then, calculation methods are identified and boundary conditions are determined.

3.1 Building Selection

In Turkey, heating energy consumption accounts 33% of total energy [6]. Besides, residential buildings consume 32% of total energy.TS 825 standard which determines thermal insulation requirements for buildings was published in 1999 [5]. However, inadequencyof insulation study for buildigs gave birth to excessive heat loss from buildings [6]. Besides, lack of commissioning process prevents to going further.

This dissertationstudies a twin unit, a twin unit two story building located in Manisa Turkey.

3.2 Identification of Environmental Site

Environmental site is an important issue when it comes to energy modelling of building. Hourly temperature data, average wind speed and solar radiation of district effects simulation results.

Weather data taken from General Directorate of Meteorology.

3.3 Identification of Building Characteristics

In order to conduct a thermal bridge study, envelope details in terms of dimensions of building and materials must be known to evaluate k values. k value is a physical property of matearial which determines thermal transmittance, and expressed in W/mK with respect to SI unit system.

On the basis of surface temperature calculation results relationship between thermal bridge and indoor environmental quality is evaluated. In detail, the effects of precence of mold growth on indoor surface on indoor air quality is clarified. Moreover thermal bridge effects on building durability is explained briefly.

Overall energy performance of the buiding is calculated based on the architectural, mechanical and electrical systems as well detailed specifications about these building systems. Identification of The Problematical surfaces in the Building in Terms of Thermal Bridge

Thermal bridge can be defined as; a part of building envelope that thermal transmittance changed by material transition or thickness uniformity [19].

Thermal bridge may occur on building envelope in different reginons. EN 14683 classifies thermal bridges in eight main categories as listed below [20]:

- Roof thermal bridges
- Balcony thermal bridges
- Corner thermal bridges
- Intermediate floor thermal bridges
- Intermediate wall thermal bridges
- Ground floor thermal bridges
- Pillar thermal bridges
- Window and door opening thermal bridges

In this study balcony thermal bridges are investigated.

3.4 Identification of Calculation Methods

In this section calculation methods which are used in this study are explained in detail. Numeric calculation of thermal bridges are explained in EN 10211:2007 standard [19].

The calculation process starts with development of exterior wall's U-values on the basis of internal and external surface resistances and wall material's thermal conductivity values. Followed by, linear thermal transmittance values for balcony slab are calculated. Depending on linear thermal transmittance values, overall U values of envelope are determined. Then, calculation of building energy performance in terms of heating, cooling and total energy consumption is performed.

Following section describes the calculation methods for thermal bridge.

3.4.1 Heat transfer

Heat is a form of energy and transfers from high temperature to low temperature region and stops when two mediums reach the same temperature. This situation called as thermal equilibrium.. Heat transfer is a science which deals with determination of rates of heat transfer [23].

Heat transfer can be occured in three way such as; conduction, convection and radiation.

3.4.1.1 Convection

Convection is a type of heat transfer between solid surface and adjacent fluid motion. It comprises effects of conduction and convection as well [23].

Rate of fonvection heat transfer can be expresses as following formula;

$$\dot{Q} = hA_s \left(T_\infty - T_s\right) \tag{3.1}$$

Where, h is convection heat transfer coefficient in W/m^2, A_s is surface area in m^2, $T_{\infty,s}$ is boundary temperatures in $K, \dot{Q}$ is rate of convection heat transfer in W.

3.4.1.2 Radiation

Changes in electronic configurations of atoms or molecules resulted in electromagnetic waves. The form of electromagnetic wave or photon are called radiation [23].

Rate of radiation heat transfer can be expressed as following formula;

$$\dot{Q} = \varepsilon \sigma A_s T_s^4 \tag{3.2}$$

Where, ε is emissivity of surface, σ stefan-boltzman constant in W/m^2K^4, T_s is surface temperature in K.

3.4.1.3 Conduction

Energy transfer that can take place in solids, liquids and gases from high energy substance to adjacent low energy substance is defined as conduction. Amount of conduction depends on geometry of material, thickness of material and physical properties of material. Experiments have proved that; heat conduction through a plane increases with the temperature difference across the layer and the raise in heat transfer area. However, conduction decreases with the increase in thickness of the layer [23].

Following figure illustrates heat transfer via conduction.

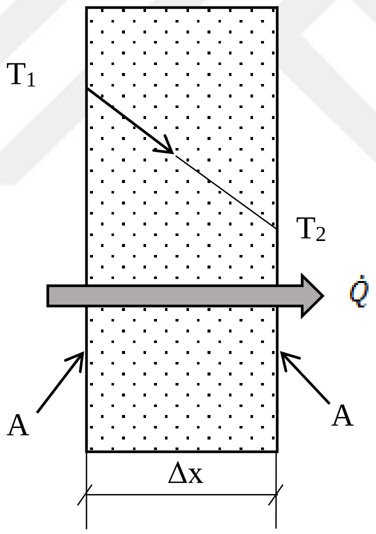


Figure 3.2 : Conduction heat transfer through a plane wall.

$$\dot{Q}_{cond} = kA\frac{T_1 - T_2}{\Delta x} = -kA_s\frac{\Delta T}{\Delta x} \tag{3.3}$$

Where, k is thermal conductivity of material in $W/m°C$, $T_{1,2}$ is boundary temperatures in $°C$, Δx is thickness of the plane wall in m.

Steady state heat conduction in plane walls

Considering a heat conduction through a building wall in winter season. Heat transfer occurs from hot indoor space to cold ambient space depending on temperature difference between indoor and outdoor ambient. Besides, heat transfer through the wall is in normal direction to the wall surface. If air temperatures are assumed constant for inside and outside spaces, heat transfer can be modelled as steady state and one dimensional. In this case, temperature of the wall is a function of wall length [23].

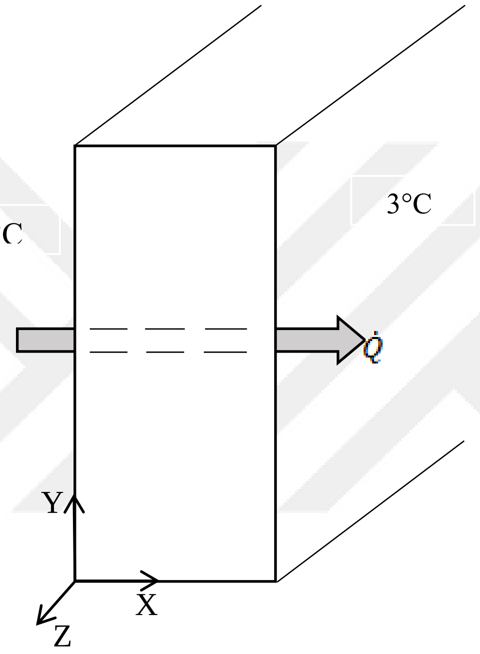


Figure 3.3 : Heat transfer through a plane wall.

Energy balance of the wall can be drawn as;

$$\dot{Q}_{in} - \dot{Q}_{out} = \frac{dE_{wall}}{dt} \tag{3.4}$$

Where, dE_{wall} / dt is rate of change of energy of the wall in *W*.

The temperature in steady state conditions does not change with time. Thus, the rate of change of energy of the wall must be equal to zero. This means that, $\dot{Q}_{cond,wall}$ is constant.

Consider a plane wall of thermal conductivity *k*, thickness *L*. Inner and outer surface of the wall maintained at constant temperatures as T_1 and T_2. For one dimensional steady state heat conduction through the wall we have $T(x)$. Thus, Fourier's heat conduction law can be expressed as;

$$\dot{Q}_{cond,wall} = -kA_s \frac{dT}{dx} \tag{3.5}$$

Where, *dT/dx* is temperature change with x direction in *°C*.As it is mentioned above, $\dot{Q}_{cond,wall}$ is constant. Thus, *dT/dx* must be constant as well. This means that temperature through the wall varies linearly with *x*.

If we integrate the Fourier's equation from $x=0$ where $T(0)=T_1$, to $x=L$ where $T(L)=T_2$ we will get;

$$\int_{x=0}^{L} \dot{Q}_{cond,wall}\,dx = -\int_{T=T_1}^{T_2} kA\,dT$$

Integration yields us;

$$\dot{Q}_{cond,wall} = kA_s \frac{T_1 - T_2}{L} \tag{3.6}$$

Again, the formula above suggests that, thermal conductivity, wall area and temperature difference are proportional to heat conduction, however, heat conduction is inversely proportional to wall thickness.

3.4.2 Thermoelectrical analogy

Thermoelectrical analogy considers the heat flow as current and walls as resistances. On the basis of thermoelectrical analogy, U values of building envelope may be calculated as following [23];

$$R_{wall} = \frac{L}{kA_s} \tag{3.7}$$

Where, *L* is thickness of plane wall in m, R_{wall} is thermal resistivity of plane wall in *K/W*.

$$\dot{Q}_{cond,wall} = \frac{T_1 - T_2}{R} \quad (3.8)$$

Where, R is thermal resistivity of plane wall in *K/W*, $\dot{Q}_{cond,wall}$ is heat transfer through plane wall in *W*.

$$R_{conv} = \frac{1}{hA_s} \quad (3.9)$$

Where, R_{conv} is convection resistance of surface in *K/W*.

Following figure illustrates thermoelectrical analogy for plane walls.

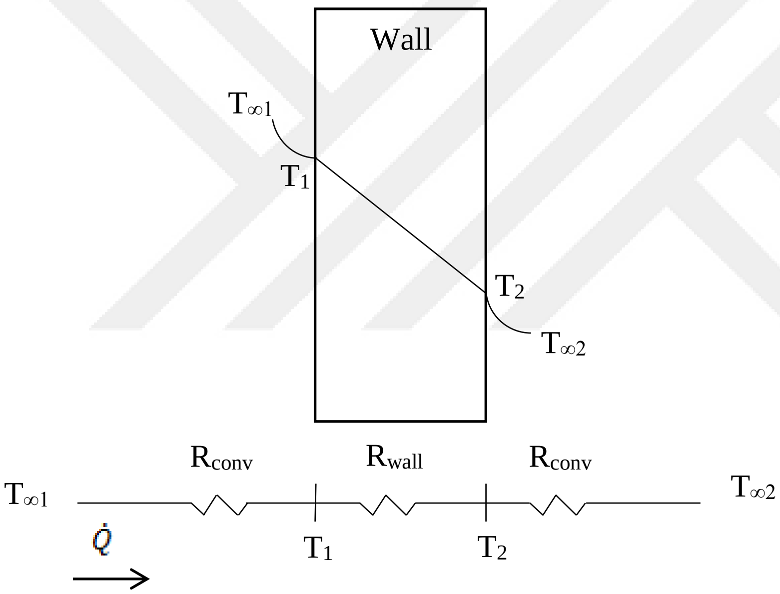


Figure 3.4 : Thermoelectrical analogy.

$$R_{total} = R_{conv,1} + R_{wall} + R_{conv,2} = \frac{1}{h_1 A} + \frac{L}{kA} + \frac{1}{h_2 A} \quad (3.10)$$

$$\dot{Q} = \frac{T_1 - T_2}{R_1 + R_{wall} + R_2} \quad (3.11)$$

$$\dot{Q} = UA\Delta T \quad (3.12)$$

$$UA = \frac{1}{R_{total}} \tag{3.13}$$

3.4.3 Calculation of linear thermal transmittance

European standard EN 10211:2007 describes the calculation of linear thermal transmittance as follows [19];

$$\psi = L^{2D} - \sum_{j=1}^{N} U_J l_j \tag{3.14}$$

Where, Ψ linear thermal transmittance of the linear thermal bridge separating two environments in *W/mK*, U_J is thermal transmittance of the 1-D component of j separating the two environments in *W/m²K*, l_j is length within 2-D geometrical model over which the value U_J applies in m, N is number of 1-D elements.

$$L_{2D} = \frac{\phi_l}{\Theta_i - \Theta_e} \tag{3.15}$$

Where, L_{2D} is thermal coupling coefficient in *W/mK*, ϕ_l is heat flow rate per meter length in *W/m*, Θ_i is internal temperature in *K*, Θ_e is external temperature in *K*.

3.4.4 Calculation of overall U value

In order to obtain overall U value, linear thermal transmittance values are calculated which indicates thermal transmittance of thermal bridge area. Overall U value can be calculated as follows [8];

$$U = \frac{\sum(\psi.L) + \sum(\chi)}{A_{Total}} + U_0 \tag{3.16}$$

Where, U is total effective assembly thermal transmittance in W/m^2K, U_0 is clear field thermal transmittance in $W/m^2\ K$, A_{Total} is total opaque wall area in m^2, Ψ is linear thermal transmittance in *W/mK*, L is length of thermal bridge in m, χ is heat flow from point thermal bridge in *W/mK*.

Effects of point thermal bridges are neglected throuhout this study.

3.4.5 Calculation of surface temperature factor

Surface temperature factor is used to evaluate condensation potential at a specific point. EN 10211-2007 suggests to calculate surface condensation potential to eliminate mold grow [19].

Surface condensation potential is an dimensionless number. Each country develops own evaluation chart on the basis of their climatical conditions to use in design phase and/or retrofitting phase.

Minimum surface temperature factor is suggested as 0.75 for dwellings in order to avoid mold growth [24]. However, TS 825 does not suggest any value for surface temperature factor.

$$f_{Rsi}(x,y) = \frac{\Theta_{si}(x,y) - \Theta_e}{\Theta_i - \Theta_e} \tag{3.17}$$

Where, f_{Rsi} is temperature factor for the surface at point *(x,y)*, $\Theta_{si}(x,y)$ is temperature for the internal surface at point *(x,y)*, in *K*.

3.4.6 Boundary conditions

EN 6946:2007 describes the calculation methods of thermal transmittance and thermal resistance. The standard suggests surface resistances in terms of heat flow direction as follows [21];

Table 3.1 : Surface resistance values.

	Direction of heat flow		
Surface resistance [W/m^2K]	Upwards	Horizontal	Downwards
R_{si}	0.10	0.13	0.17
R_{se}	0.04	0.04	0.04

In this study, heat flow is horizontal because of indoor space temperatures are equal. Therefore, indoor surface resistance is chosen as 0.13 W/m^2K, exterior surface temperature is chosen as 0.04 W/m^2K however, this value is equal for all directions as shown in the table above.

As regards to indoor temperature, 20°C is selected for winter season on the basis of EN 15251 and Ashrae-55. EN 15251 suggests that, design temperatures for heating ventilating and air conditioning (HVAC) systems 20°C for 1.0 clo and 1.2 met values [25, 26].

Outdoor temperature is decided as 0°C depending on site's annual temperature statistics [27].

Following figure illustrates surface resistances of indoor and outdoor space of the case study'thermal bridge geometry.

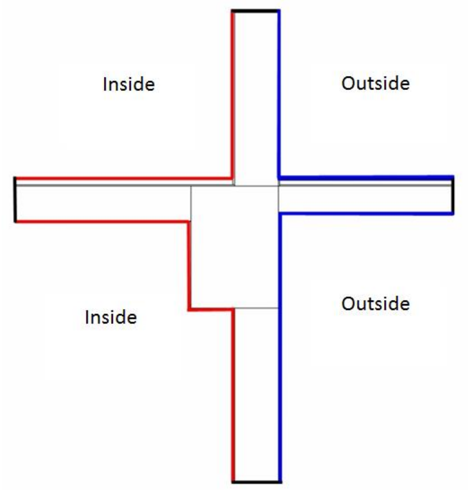


Figure 3.5 : Boundary spaces of selected geometry.

3.5 Assesment of Building Energy Performance

In order to evaluate thermal bridge effect on building energy performance, linear thermal transmittance is calculated by Therm 7.3 software. Then, overall U value is derived and inputted into the eQuest software. Building energy performance is being examined by eQuest results.

3.5.1 Introduction to Applied Software

3.5.1.1 Therm 7.3

THERM is a freeware steady state finite element two dimensional heat transfer software released by Lawrance Berkeley National Laboratory [28]. The tool's user interface allows users to draw their own geometries or import CAD drawings such as .dxf files or bitmap files (.bmp) [29]. Material database of software initially consists of default building elements mostly glazing and door materials but users can create specific materials simply by entering material’s thermal conductivity and emissivity for a definite simulation. Besides, addition or subtraction of boundary conditions is possible as well. By entering temperature, film coefficient and relative humidity a boundary condition can be created as well.

The tool is capable of generate mesh automatically and users can alter mesh parameters due to error estimator [30].

Following results can be seen after THERM heat transfer simulation;

1. Isotherms;
2. Color-flooded isotherms;
3. Het flux vector plots;
4. Color-flooded lines of constant flux;
5. Temperatures (local and average, maximum and minimum);
6. Total product U-factor.

Following figure illustrates user interface of Therm software.

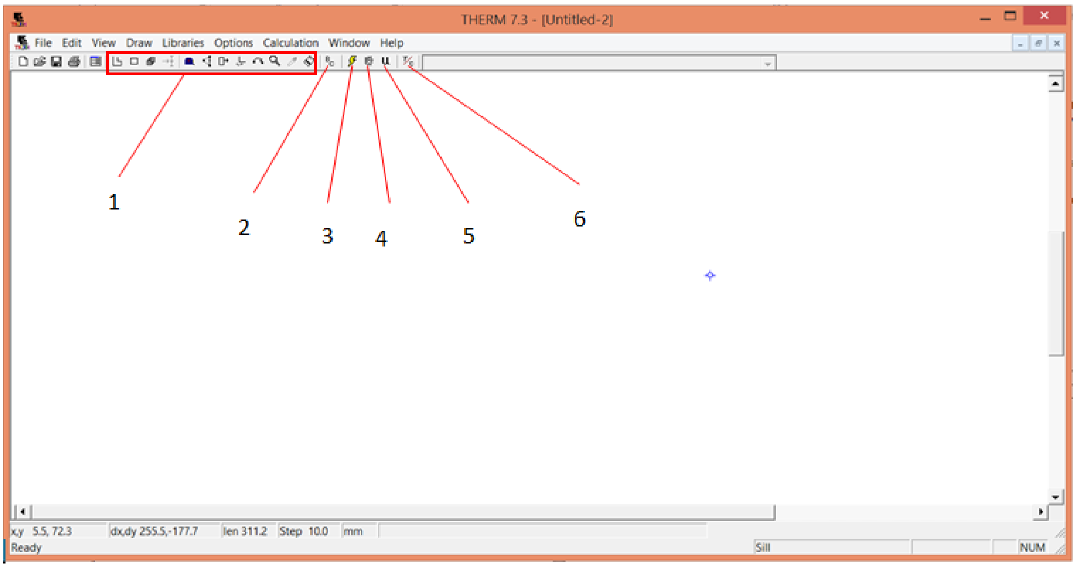


Figure 3.6 : User interface of Therm 7.3.

Features which numbered on the figure above;

1. Drawing and measurement tool

2. Boundary condition selection

3. Calculation

4. Show/hide results

5. U-values and heat flows

6. Unit conversion

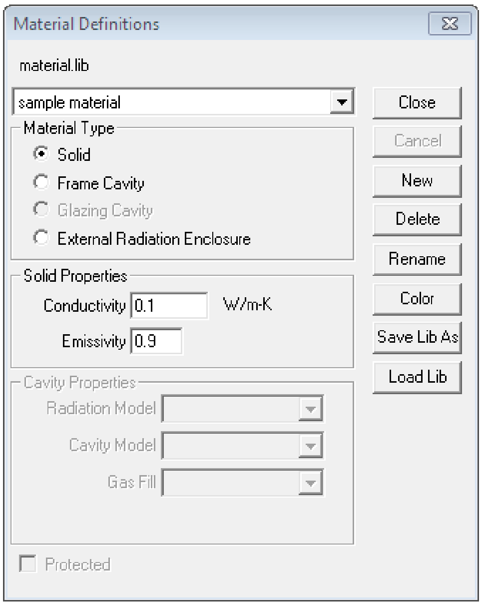


Figure 3.7 : New material addition window of Therm 7.3.

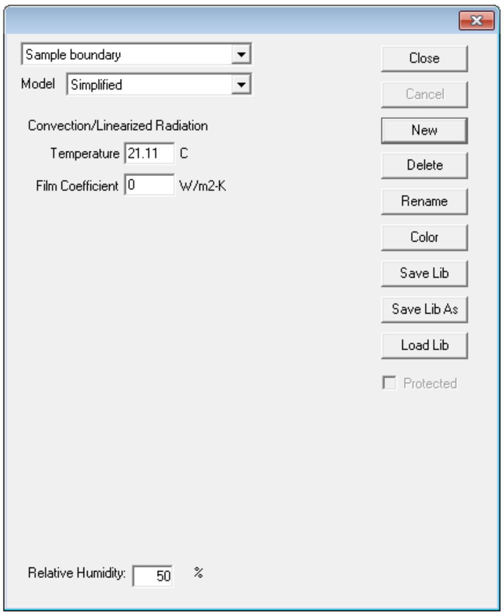


Figure 3.8 : New Boundary condition window of Therm 7.3.

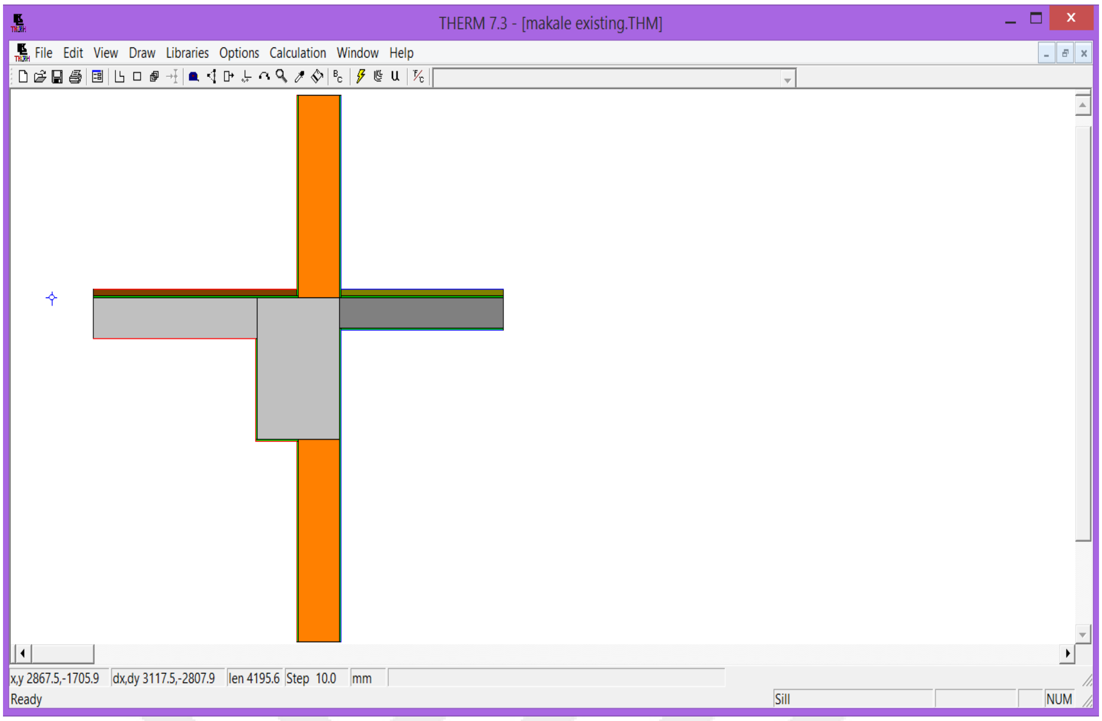


Figure 3.9 : Therm 7.3 model of selected thermal bridge geometry.

Two dimensional heat transfer analyses for balcony geometry was calculated using THERM program. U-values which calculated by THERM were inputted into eQUEST software.

EN 20211:2007 validation of Therm 7.3 software

In order to validate data obtained from finite element software, EN 10211-2007 suggests four tests for 3D analysis and two tests for 2D analysis. Which are [19];

Case-1: Heat transfer through half square column with known surface temperatures;

Case-2: Heat transfer through composite wall with known surface temperatures.

Following sections describe each validation test and test results for Therm 7.3 software.

EN 10211:2007 validation for case-1

Heat transfer through half a square column with known surface temperatures was considered. Temperature of 28 nodes are calculated analytically for a material which thermal conductivity is 1 *W/mK* within the standard. It is suggested that, temperature difference between standard and validation test should not exceed $0.1°C$ [19].

Following figure illustrates boundary condition of column and analytically calculated temperatures of 28 nodes.

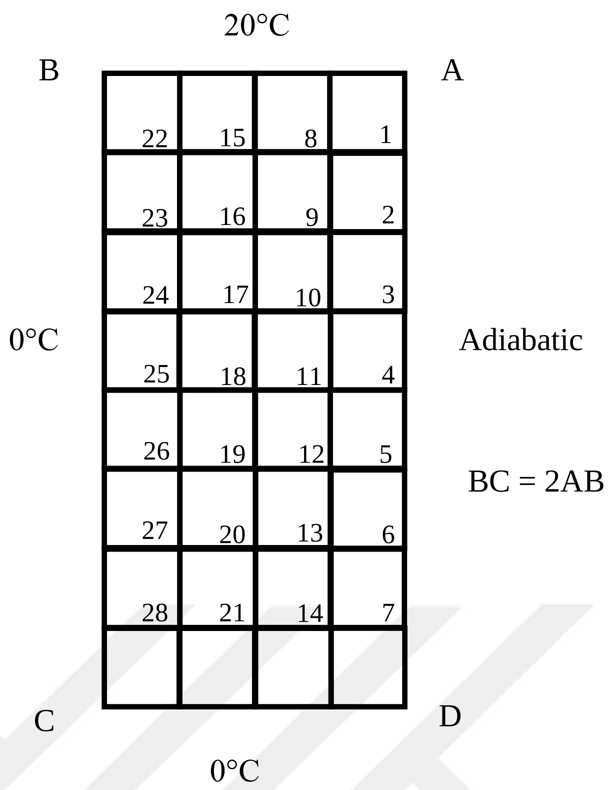


Figure 3.10 : Nodes of EN 10211:2007 validation case-1.

Table 3.2 : Node temperatures of EN 10211:2007 validayion test for case-1.

Number of node	Temperature [$°C$]
1	15.1
2	10.8
3	7.5
4	5.0
5	3.2
6	1.9
7	0.9
8	14.7
9	10.3
10	7.0
11	4.7
12	3.0
13	1.8
14	0.8
15	13.4

Table 3.2 (continued): Node temperatures of EN 10211:2007 validayion test for case-1.

Number of node	Temperature [°*C*]
16	8.6
17	5.6
18	3.6
19	2.3
20	1.4
21	0.6
22	9.7
23	5.3
24	3.2
25	2.0
26	1.3
27	0.7
28	0.3

EN 10211:2007 validation for case-2

Case-2 considers a composite wall consist of four building materials which are; concrete, wood, insulation and aluminum. The standard suggest that, difference between standard's values and validation test values for temperature should not exceed 0.1°*C* also for heat flow should not exceed 0.1 *W/m* [19].

On the basis of these cases validation of softvare will be performed.

Following figure illustrates case-2 model geometry.

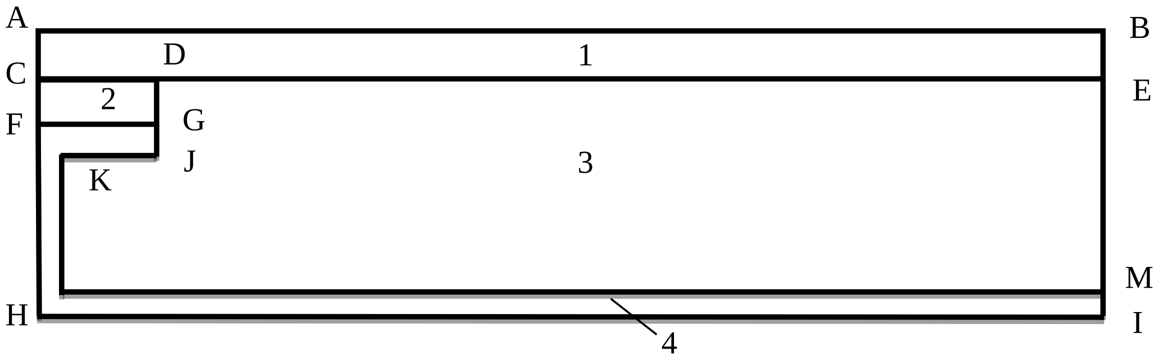


Figure 3.11 : Model of EN 10211:2007 validation for case-2.

The material coded as 1 in the figure is concrete also, number 2, number 3 and number 4 are; wood, insulation, aluminum respectively.

Following table shows dimensions of different layers, k values and surface resistance values for interior and exterior space.

Table 3.3 : Boundary conditions of EN 10211:2007 validation for case-2.

Dimensions [*mm*]	Thermal Conductivity [*W/mK*]	Boundary conditions
AB = 500	1: 1.15	AB: 0°C with R_{se} = 0.06 m^2K/W
AC = 6	2: 0.12	HI: 20°C with R_{si} = 0.11 m^2K/W
CD = 15	3: 0.029	
CF = 5	4: 230	
EM = 40		
GJ = 1.5		
IM = 1.5		
FG – KJ = 1.5		

3.5.2 Building energy performance analysis

In this study energy performance analysis of building is done by eQuest software. eQuest is a whole building dynamic building energy simulation tool built upon DOE 2-2 simulation engine developed by U.S. Department of Energy [31]. The software allow users to input detailed building data such as building type, operation schedules, U-values, chiller, pumps and boiler. Also, eQUEST allows users to import CAD files to calculate exact sizes of zones.

Initially, software has weather data for US but users can add a specific weather data with .bin format. Latitude of the building need to be determined in order to obtain appropriate hourly weather data of the district longitude [32].

eQUEST presents a detailed hourly report for a year and graphical summary results. Users can check loads and energy consumption of individual spaces. Also, energy consumption HVAC system elements such as a pump or chiller can be found in the output file.

Our case study buildings energy model was created with eQUEST on the basis of building data and THERM outputs.

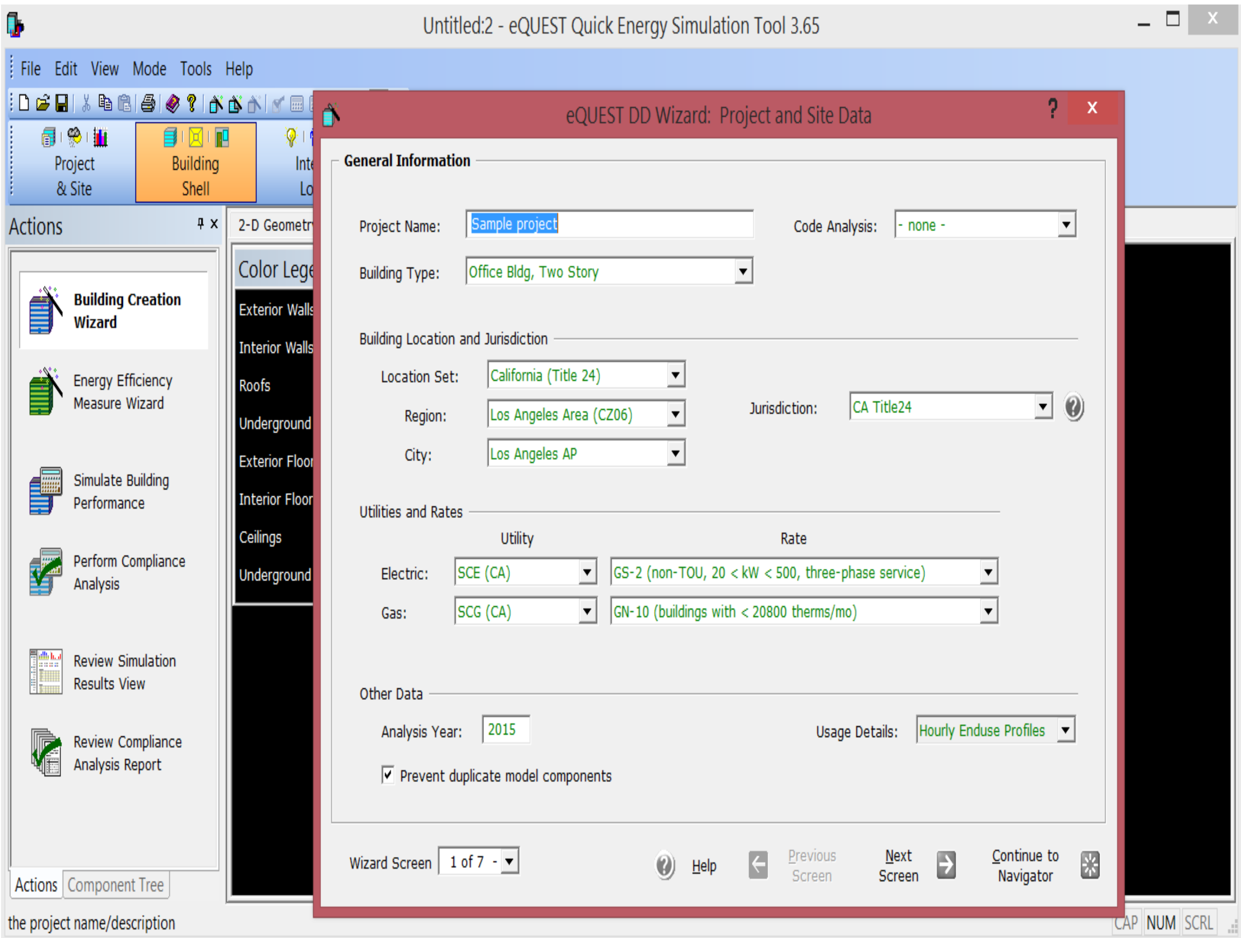


Figure 3.12 : User interface of eQuest software.

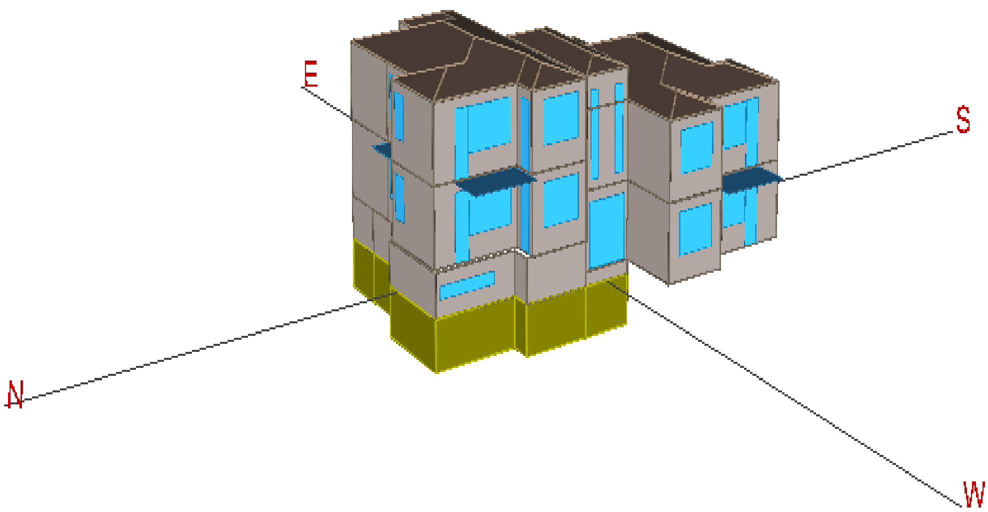


Figure 3.13 : eQuest model of our building.

4. CASE STUDY

A case study approach was adopted to help understand the impacts of thermal bridge on building energy performance. A typical residential building was chosen for the case study in order to evaluate effects of balcony thermal bridges on building energy performance.

In this study, three case studies are investigated as listed below;

Case -1: Existing condition (uninsulated);

Case-2: Exterior wall insulated condition;

Case:-3: Exterior wall and balcony slab insulated condition.

Following table explains case studies.

Table 4.1 : Summary of case studies.

	Exterior wall	Balcony slab
Case-1	Not insulated	Not insulated
Case-2	Insulated	Not insulated
Case-3	Insulated	Insulated

4.1 Building Selection

As discussed in introduction section, residential energy consumption accounts almost a half of total energy consumption in OECD countries. With respect to fast growing trend of construction sector lack of insulation studies in Turkey, a residential building is selected.

In Turkey Building Energy Performance Management Code published in 2008 [33]. However, most of the buikldings lack of insulation study still.

Our case study building is a residential two storey twin apartment unit. Each apartment unit has 103 m^2 conditioned area.

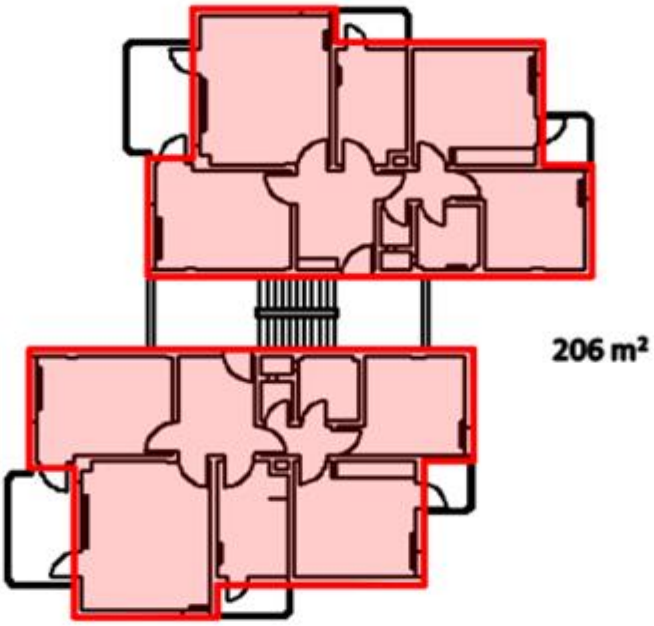


Figure 4.1 : Footprint of the selected building

As illustrated above two apartment consist of 206m^2.

Table 4.2 : Description of selected building.

Description	Details	
Two story residential building with 412 m^2 conditioned area	Façade area (windows and doors excluded)	445.258 m^2
	Length of balcony slab contacted surface	25.4 m
	Window and door area	63.87 m^2

Figure 4.2 : A photograph of selected building.

4.2 Identification of the Environmental Site

The building is located in Soma which is town of Manisa Province located in Aegean district of Turkey. Major characteristics of the Soma is given in table below [34];

Table 4.3 : Details of Soma district.

Total area	826 km^2
Population in city center	60,674
Elevation from sea level	175m

Figure 4.3 : Location of Manisa Province in Turkey.

Climate type of Soma is Mediterranean climate. Following graphics illustrates temperature precipitation values of Soma on a monthly basis.

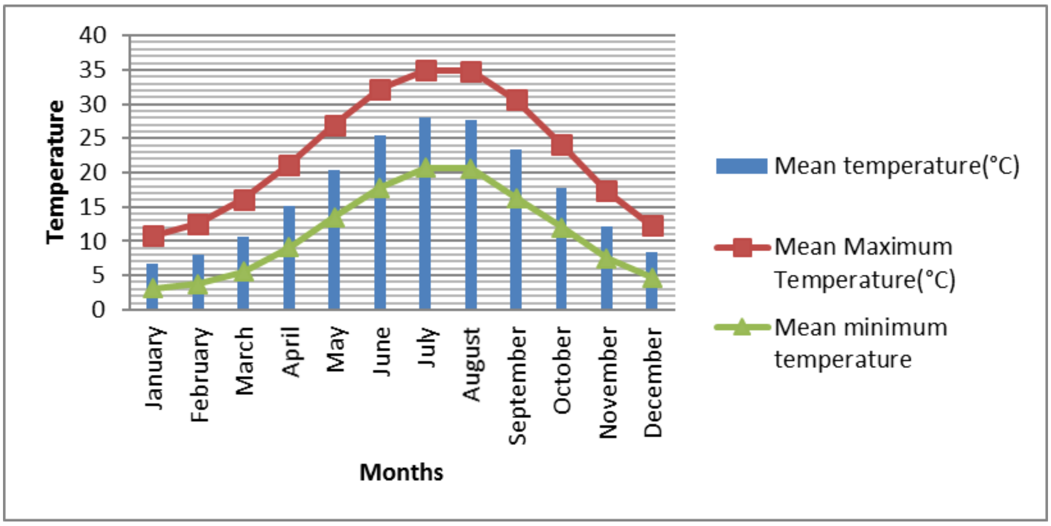


Figure 4.4 : Annual temperature graph of Manisa district.

As shown in the figure 4.4, average temperature may increase almost 30°C, however, the average temperature may decrease nearly 5°C. Besides, mean maximum temperature can go up to 35 degrees in summer seasons, nonethless mean minimum temperature can drop to 3 degree in winter seasons [35].

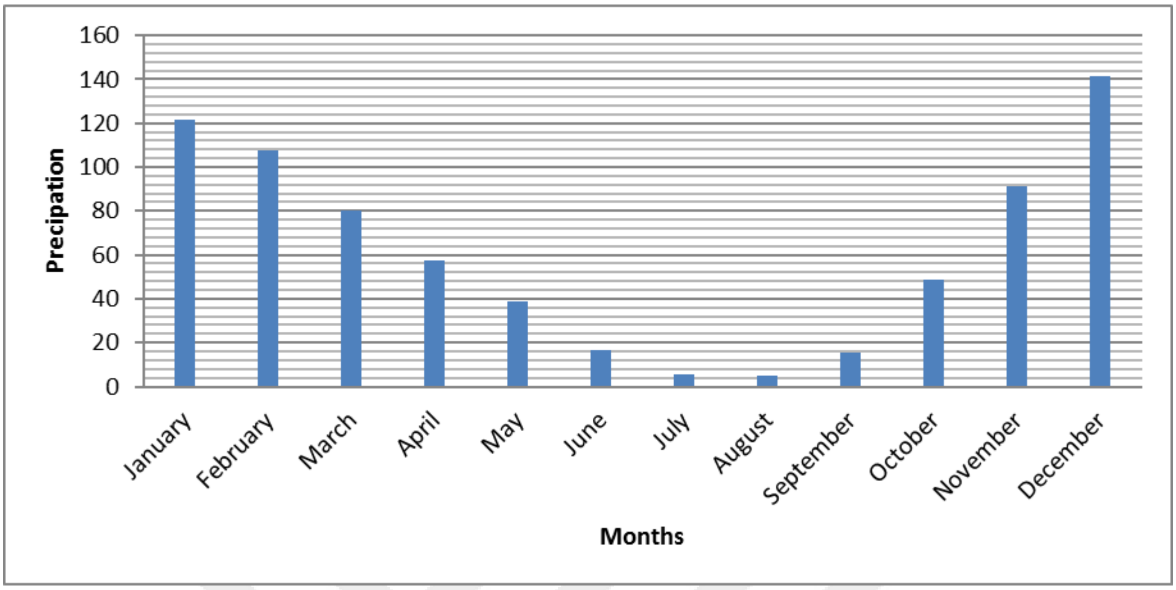


Figure 4.5 : Annual precipation values of Manisa district.

The bar chart above shows precipation of the Soma. It can be seen that, Precipation may drop nearly 0 mm in summer seasons, however, in winter seasons it increases almost 150 mm [35].

4.3 Identification of Building Characteristics

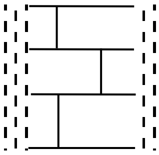
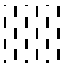
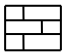
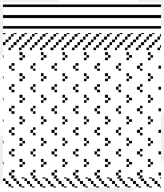
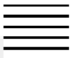
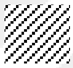
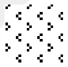
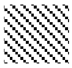
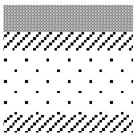
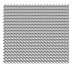
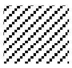
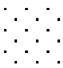
Building is constructed as single block concrete. Walls consist of brick and cement finish. Also, heating system is beased on conventional heating, besides, cooling need is provided by split air conditioner. In detail, exterior wall consists of cement finish and brick layer, internal floor consist of hardwood, cement finish, reinforced concrete, gypsym plaster layers, balcony floor consists of granite, cement finish and low reinforced concrete layers.

Following table presents characteristics of selected building section including material names and layers.

Table consists of exterior wall, internal floor and balcony floor with their thermal conductivity value of each layer.

Next section identifies problematical sites in the building in terms of thermal bridge.

Table 4.4 : Details of selected geometry.

Building element	Drawing	İllustration of individual elements	Name of material	Thermal conductivity (W/mK) [22]
Exterior wall			Cement Finish	1.4
			Brick	1.4
Internal floor			Hardwood	0.2
			Cement finish	1.4
			Reinforced concrete	2.5
			Gypsum plaster	0.51
Balcony floor			Granite	2.8
			Cement finish	1.4
			Low reinforced concrete	1.65

4.4 Identification of the Problematical Sites in the Building in Terms of Thermal Bridge

As mentioned in previous chapters thermal bridges in buildings depends on geometry and material. In this study, Balcony thermal beridges are investigated.

Following figure illustrates demo building's balcony slab cross section which used in this study.

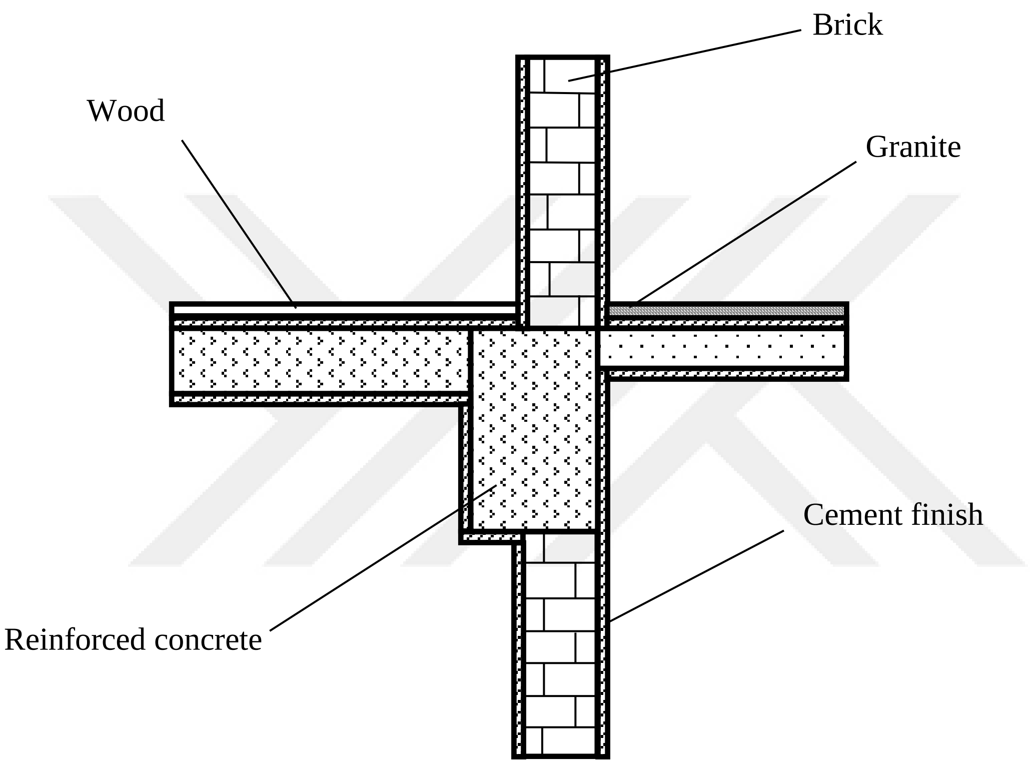


Figure 4.6 : Intersection of selected geometry.

In the figure above, left hand side represents indoor surface, right hand side represents outside.

4.5 Identification of Calculation Methods

In order to conduct a thermal bridge calcualtion numerically, validation tests of finite element software must be done on the basis of EN 10211:2007 [19]. The standard suggests four validation tests, however, for two dimensional calculation first two validation test is recommended.

Following chapter explains validation tests for this study.

4.5.1 Results of EN 10211:2007 validation test case-1 for Therm 7.3 Software

In order to evaluate 28 nodes, mentioned in previous sections, model is developed combination of 50 cm x50cm squares. For width of the column, 4 squares are combined also, 8 squares are combined for the height of column as shown below.

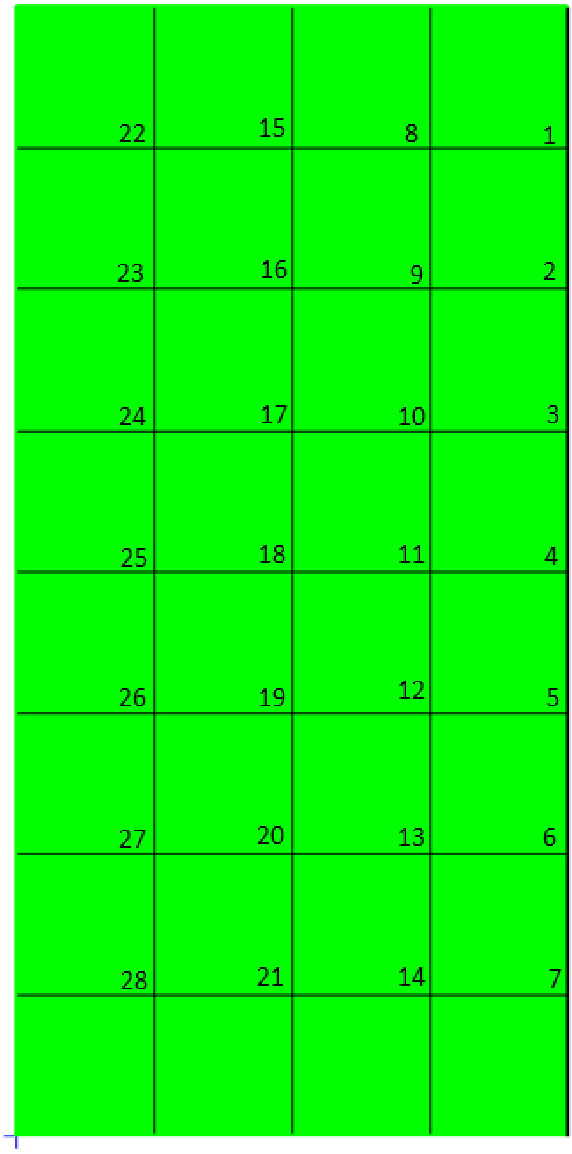


Figure 4.7 : EN 10211:2007 validation model for case-1.

Finally, 400 cm x 200 cm half a square column is developed and simulated on the basis of standard's suggestions by using Therm 7.3. As boundary temperatures; upper side of the column is set as 20°C, left hand side and bottom side is set as 0°C and right hand side of the column is set as adiabatic depending on EN 10211:2007 [19].

Following figure illustrates color infrared result of simulation.

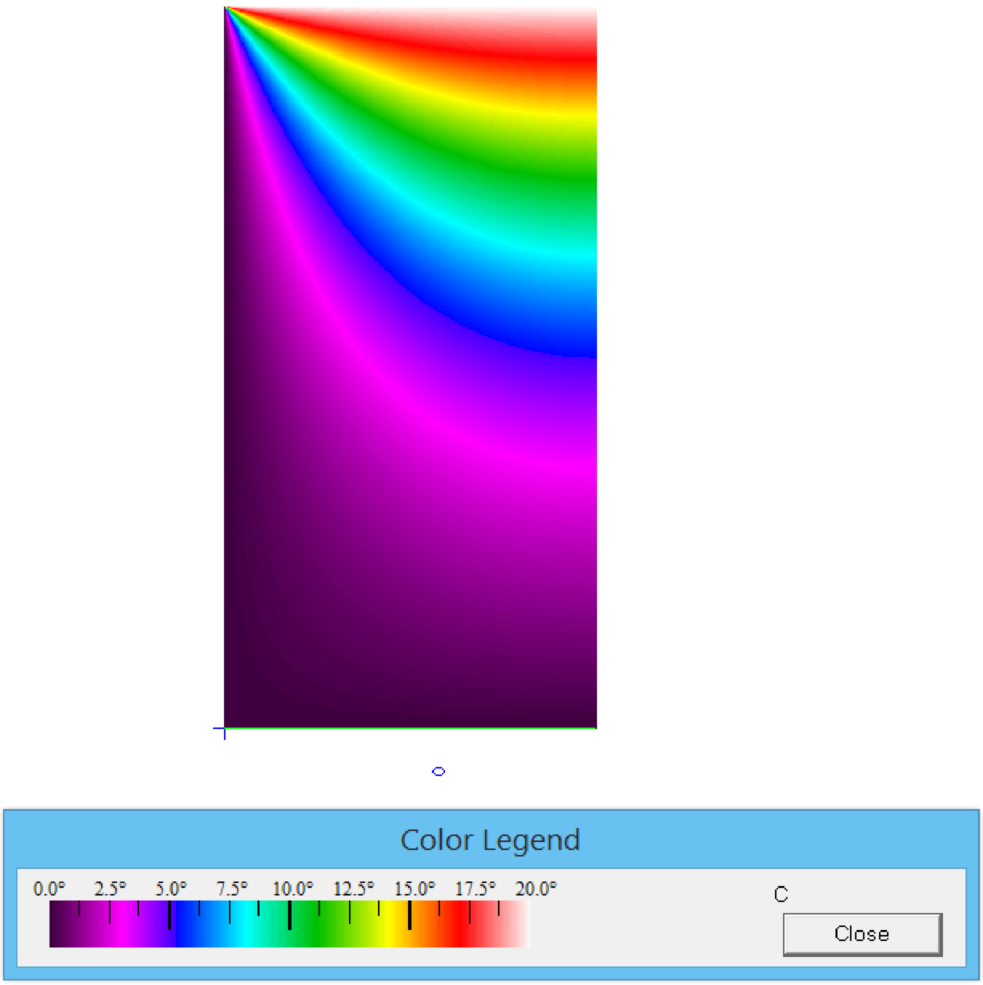


Figure 4.8 : Color infrared graph of EN 10211:2007 validation for case-1.

With regard to boundary conditions color infrared graph seem logic.

Following table presents comparison of temperature values in °C between the standard and Therm 7.3 results.

Table 4.5 : Results of EN 10211:2007 validation test for case-1.

Number of node	x-coordinate [mm]	y-coordinate [mm]	EN 2011-2007 T[°C]	Therm test results T[°C]	Difference T[°C]
1	200	350	15.10	15.09	0.01
2	200	300	10.80	10.81	0.01
3	200	250	7.50	7.46	0.04
4	200	200	5.00	5.00	0
5	200	150	3.20	3.21	0.01

Table 4.5 (continued): Results of EN 10211:2007 validation test for case-1.

Number of node	x-coordinate [mm]	y-coordinate [mm]	EN 2011-2007 T[°C]	Therm test results T[°C]	Difference T[°C]
6	200	100	1.90	1.90	0
7	200	50	0.90	0.88	0.02
8	150	350	14.70	14.73	0.03
9	150	300	10.30	10.32	0.02
10	150	250	7.00	7.01	0.01
11	150	200	4.70	4.65	0.05
12	150	150	3.00	2.98	0.02
13	150	100	1.80	1.76	0.04
14	150	50	0.80	0.81	0.01
15	100	350	13.40	13.39	0.01
16	100	300	8.60	8.64	0.04
17	100	250	5.60	5.60	0
18	100	200	3.60	3.63	0.03
19	100	150	2.30	2.30	0
20	100	100	1.40	1.35	0.05
21	100	50	0.60	0.62	0.02
22	50	350	9.70	9.65	0.05
23	50	300	5.30	5.24	0.06
24	50	250	3.20	3.18	0.02
25	50	200	2.00	2.01	0.01
26	50	150	1.30	1.26	0.04
27	50	100	0.70	0.73	0.03
28	50	50	0.30	0.34	0.04

As mentioned in previous chapters, the standard suggests maximum difference of temperature value 0.1 °C. In my test, maximum value of temperature difference is calculated by Therm 7.3 is 0.06°C for node number 23. Rest of values are very close to standard's values. However, 0.06°C is acceptable for EN 10211-2007 [19].

4.5.2 Results of EN 10211:2007 validation test case-2 for Therm 7.3 software

As mentioned widely in previous chapters, case-2 considers a composite wall which consists of four material.

Following figure illustrates model of geometry which created using Therm sorftware on the basis of standard's spesifications.

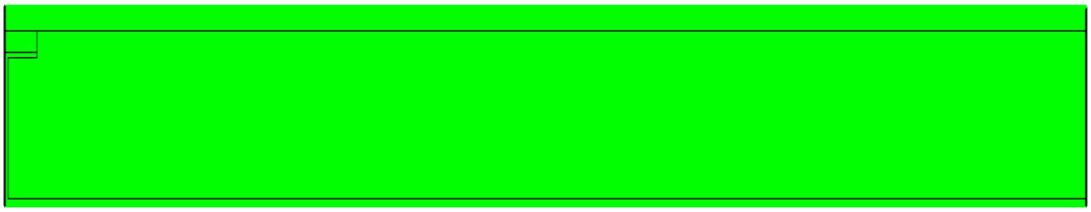


Figure 4.9 : EN 10211:2007 validation model for case-2.

Composite wall is created on the basis of four material's k value which are concrete, wood, insulation material and aluminum. Besides, dimensions are inputted due to EN 10211:2007 [19].

Following figure which is a color infrared graph presents Therm 7.3 simulation results of composite wall for validation test.

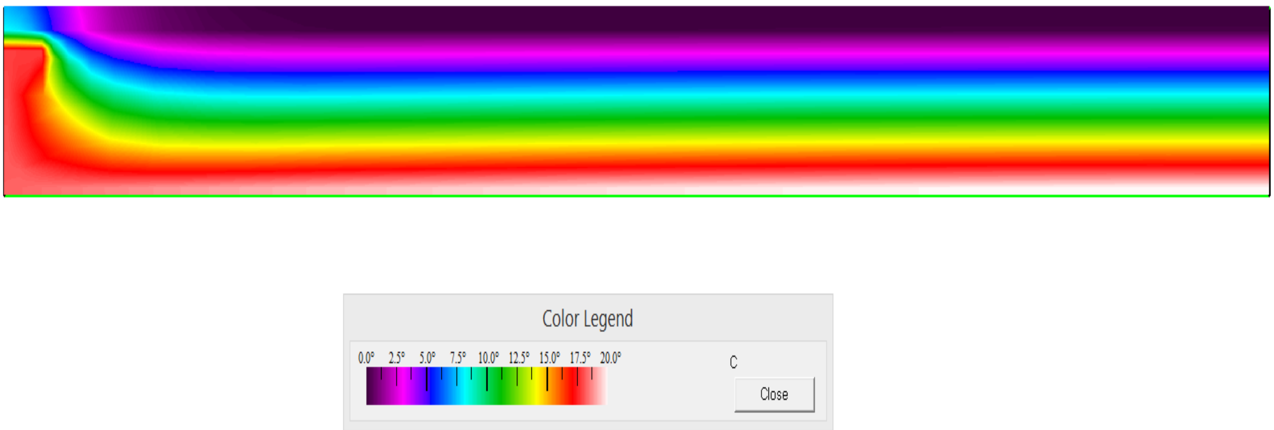


Figure 4.10 : Color infrared graph of EN 10211:2007 validation for case-2.

Bottom side of the composite wall is set as 20°*C* with 0.11 m^2K/W surface resistance and upper side of the composite wall is set as 0°*C* with 0.06 m^2K/W surface resistance. Down side of the wall represents indoor space and upper side of the wall represents outdoor surface on the basis of EN 10211:2007 [19].

Not surprisingly, left hand side of the wall is described as red color. This is because of very high thermal conductivity of aluminum material exist in section.

Following table shows difference between calculation results of the Therm 7.3 and the standard for specific points.

Table 4.6: Temperature results of EN 10211:2007 validation test for case-2.

Point	EN 2011-2007 T[°*C*]	Therm test results T[°*C*]	Difference T[°*C*]
A	7.1	7.12	0.02
C	7.9	7.93	0.03
F	16.4	16.39	0.01
H	16.8	16.75	0.05
D	6.3	6.29	0.01
G	16.3	16.32	0.02
B	0.8	0.76	0.04
E	0.8	0.82	0.02
I	18.3	18.30	0

The highest temperature difference is calculated for point H as 0.05°*C*. However, the standard suggests maximum value of temperature difference as 0.1°*C*. this shows that, temperature values are coherent with the EN 10211:2007 [19].

According to analysis results of validation, heat flow difference is calculated as 0,03 W/mK between EN 10211:2007 and Therm software analysis.

As mentioned in previous chapters, the standard suggest the maximum value of heat flow per meter as 0.1 *W/mK*. However, the difference between Therm 7.3 calculation and standard's values is 0.03 *W/mK* [19].

Taken together, these results suggest that Therm 7.3 is convenient software to calculate thermal bridges numerically on the basis of EN 10211-2007 [19].

4.6 Calculation Results

As mentioned in previous chpaters. In this study, three case studies are investigated as listed below;

Case -1: Existing condition (no insulation);

Case-2: Exterior wall insulated condition;

Case:-3: Exterior wall and balcony slab insulated condition.

Following section gives an account of calculation of thermal bridges for each three cases.

4.6.1 Calculation results for case-1

Case-1 considers the building envelope as existing situation. In this situation; no insulation is applied to the building. Basically, Exterior wall consists of brick and cement finish. Besides, Balcony slab exists of low reinforced concrete, cement finish and granite.

Following figures illustrates representative exterior wall and balcony slab.

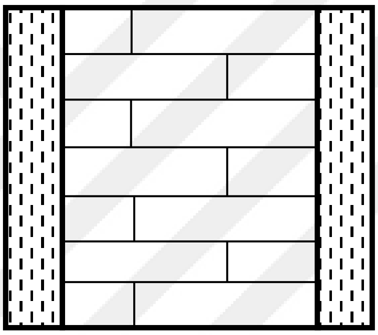
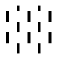
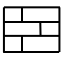


Figure 4.11 : Intersection of exterior wall.

Table 4.7: Details for exterior wall.

Representative illustration of material	Name of material	Thermal conductivity [*W/mK*]	Width of layer [*m*]
	Cement Finish	1.4	0.01
	Brick	1.4	0.25

As it can be seen in the table above, exterior wall consist of brick and cement finish.

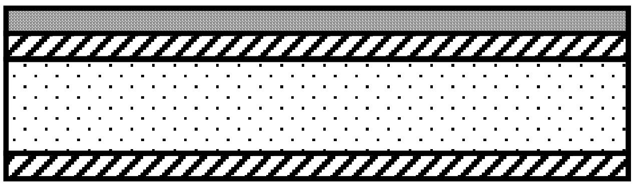


Figure 4.12 : Intersection of balcony slab.

Table 4.8 : Details of balcony slab.

Representative illustration of material	Name of material	Thermal conductivity [*W/mK*]	Width of layer [*m*]
	Granite	2.8	0.03
	Cement finish	1.4	0.01
	Low reinforced concrete	1.65	0.15

As showed in the table above, balcony slab is consists of three layers as; granite, cement finish and low reinforced concrete.

4.6.1.1 Calculation of exterior wall's U value

Based on the thermoelectrical analogy which explained in detail in previous sections, U value of exterior wall is calculated as following.

As first step, thermal resistances of each layer is calculated using equation 3.6. Thermal resistance of cement finish and brick are calculated as 0.007 m^2K/W and 0.178 m^2K/W then, total thermal transmittance of wall is calculated using equation 3.10. Total thermal transmittance of wall is calculated as 0.362 m^2K/W, lastly, U value of wall is yielded using equation 3.13. U value of wall is calculated as 2.762 m^2K/W.

Length of each layers and k values are demonstrated in section 4.6.1 and area of wall is taken as 1 m^2.

Following figure illustrates thermal resistance model for case-1.

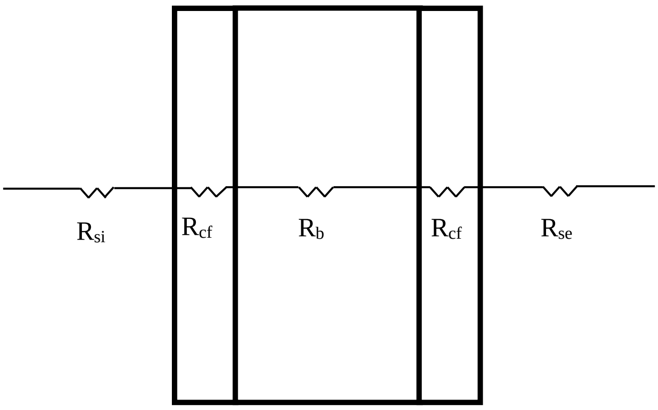


Figure 4.13 : Thermal resistance model of exterior wall.

Calculation of linear thermal transmittance

In order to evaluate heat loss through walls and balcony slab and calculate linear thermal transmittance, the geometry is created and boundary condition is defined as mentioned in previous chapters .

According to Therm analysis, heat flow is calculated as 154.614 *W/m* for 20*°C* degree difference.

Heat flow per meter celcious degree is calculated equation 3.15. Heat flow per meter celcious degree is calculated as 7.73 *W/m°C*, then linear thermal transmittance is calculated using equation 3.14. Linear thermal transmittance is calculated as 0.833 *W/m°C*. U value of wall is taken from section 4.6.1.2 and length is taken as 1m.

Calculation of overall U value of exterior wall

In order to calculate overall U value equation 3.16 is used. Linear thermal transmittance is taken from previous section however, point thermal bridges are neglected. Area of wall is demonstrated in section 4.1, besides, U value of wall is taken from section 4.6.1.2. Overall U value of wall is calculated as 2.802 $W/m^2 °C$.

Calculation of surface temperature factor

In order to calculate surface temperature factor equation 3.17 is used. Minimum temperature on the surface is calculated as 11.59*°C* using Therm software, exterior temperature is taken as 0*°C* and indoor space temperature is taken as 20*°C*.

Surface temperature factor is calculated as 0.579.

4.6.2 Calculation results for Case-2

Case-2 considers exterior wall insulated condition. Only difference between case-1 and case-2 is insulation of exterior wall.

The insulation material is selected as expanded polystyrene (EPS) which is the most common insulation material in Turkish market. Thermal conductivity EPS is selected as 0.035 *W/mK* on the basis of TS 825 standard.

A representative illustration of exterior wall for case-2 which icludes insulation layer is given below.

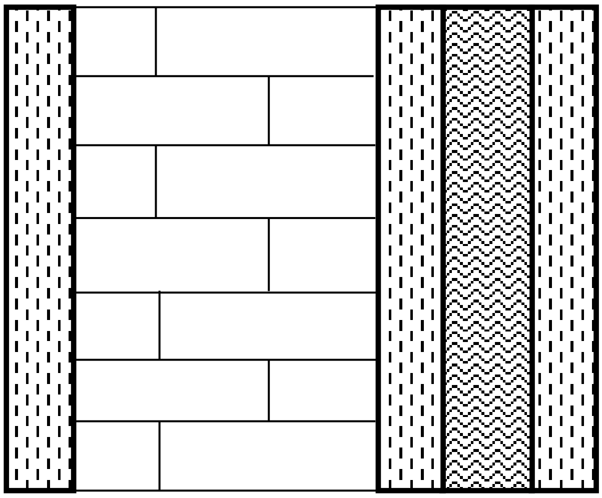
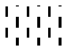
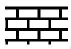


Figure 4.14 : Intersection of insulated exterior wall.

Table 4.9 : Details of insulated wall.

Representative illustration of material	Name of material	Thermal conductivity [*W/mK*]	Width of layer [*m]*
	Cement finish	1.4	0.01
	Brick	1.4	0.25
	EPS	0.035	0.05

As it can be seen in the table above, exterior wall consist of cement finish, brick and EPS insulation.

4.6.2.1 Calculation of exterior wall's U value

Based on the thermoelectrical analogy, which explained in detail in previous sections, U value of exterior wall is calculated as following.

As first step, thermal resistances of each layer is calculated using equation 3.6. Thermal resistances of cement finish layer and brick layer are taken from section 4.6.1.2 also, thermal resistance of insulation layer is calculated as 1.428 m^2K/W. Then, total thermal transmittance of wall is calculated using equation 3.10. Total thermal transmittance of wall is calculated as 1.797 m^2K/W, Lastly, U value of wall is yielded using equation 3.13. U value of wall calculated as 0.556 W/m^2K. Length of each layers and k values are demonstrated in section 4.6.2 and area of wall is taken as 1 m^2.

Following figure illustrates thermal resistance model for case-2.

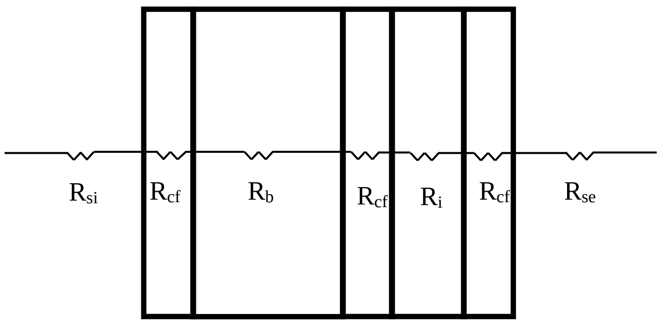


Figure 4.15 : Thermal resistance model of insulated exterior wall

Calculation of linear thermal transmittance

In order to evaluate heat loss and calculate linear thermal transmittance to obtain overall U value of the exterior wall for insulated wall case, model for Case-2 is developed in Therm 7.3. Differently from case-1, EPS insulation is mounted to the exterior wall. Thus, a decrease in U value of exterior wall is expected.

According to Therm analysis heat flow is calculated 51.198 *W/m* for 20*°C* degree difference.

Heat flow per meter celcious degree is calculated equation 3.15. Heat flow per meter celcious degree is calculated as 2.56 *W/m°C*. Then linear thermal transmittance is calculated using equation 3.14. Linear thermal transmittance of wall is calculated as 1.203 *W/m°C*. U value of vall is taken from section 4.6.2.1 and length is taken as 1*m*.

Calculation of overall U value of exterior wall

In order to calculate overall U value equation 3.16 is used. Linear thermal transmittance is taken from previous section however, point thermal bridges are neglected. Area of wall is demonstrated in section 4.1, besides, U_0 value of wall is taken from section 4.6.2.1. Overall U value of wall is calculated as 0.602 $W/m^2°C$.

Calculation of surface temperature factor

In order to calculate surface temperature factor equation 3.17 is used. Minimum temperature on the surface is calculated as 16.13*°C* by Therm software, exterior temperature is taken as 0*°C* and indoor space temperature is taken as 20*°C*. Surface temperature factor is calculated as 0.806.

4.6.3 Calculation results for Case-3

Case-3 considers insulation of exterior wall and balcony slab both. Difference between Case-2 and case-3 is insulation of balcony slab.

As an insulation material EPS is selected for exterior wall, bottom and right hand side of the balcony slab. But, for upper side of balcony slab XPS is selected due to higher compression strength of XPS compared with EPS [36, 37]. Thermal conductivity of XPS is selected as 0.030 *W/mK* on the basis of TS 825 standard.

Representative illustrations of balcony slab is presented below.

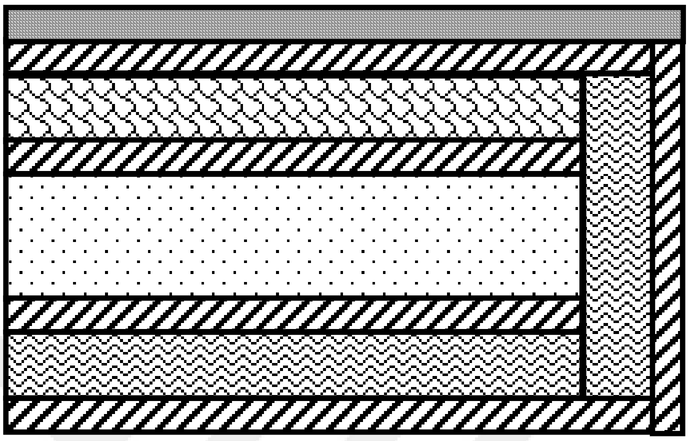


Figure 4.16 : Intersection of insulated balcony slab.

Table 4.10: Details of insulated balcony slab.

Representative illustration of material	Name of material	Thermal conductivity [*W/mK*]	Width of layer [*m*]
	Granite	2.5	0.05
	Cement finish	1.4	0.01
	Brick	1.4	0.25
	EPS	0.035	0.05
	XPS	0.030	0.05

As it can be seen in the table above, insulated balcony slab consist of five layers as; granite, cement finish, brick, EPS and XPS insulation.

Next section includes calculation of U value for exterior wall on the basis of material properties which listed above.

4.6.3.1 Calculation of exterior wall's U value

In order to evaluate heat loss through walls, floor and and balcony slab, case-3 is developed with balcony slab insulation.

According to Therm analysis heat flow is calculated 30.677 *W/m* for 20°C difference.

Because of exterior wall is the same with case-2, same U value is taken for this case.

Calculation of linear thermal transmittance

In order to obtain linear thermal transmittance heat flow per meter celcious degree is calculated equation 3.15. heat flow per meter celcious degree is calculated as 1.533 *W/m°C,* then linear thermal transmittance is calculated using equation 3.14. Linear thermal transmittance of wall is calculated as 0.177 *W/m°C*. U value of wall is taken from section 4.6.3.1 and length is taken as 1*m*.

Calculation of overall U value of exterior wall

In order to calculate overall U value equation 3.16 is used. Linear thermal transmittance is taken from previous section however, point thermal bridges are neglected. Area of wall is demonstrated in section 4.1, besides, U value of wall is taken from section 4.6.3.1. Overall U value of wall is calculated as 0.544 $W/m^2°C$.

Calculation of surface temperature factor

In order to calculate surface temperature factor equation 3.17 is used. Minimum temperature on the surface is calculated as 17.71*°C* by Therm software, exterior temperature is taken as 0*°C* and indoor space temperature is taken as 20*°C*. Surface temperature factor is calculated as 0.885.

4.7 Assessment of Building Energy Performance

In this section, 2-dimensional heat transfer simulations are performed and based on ovearall U values which calculated on the basis of linear thermal transmittance values building energy performance study is conducted. In order to investigate building energy performance, eQuest software is used.

As mentioned in previous chapters, Therm is a 2-Dimensional based finite element heat transfer analysis tool developed by Berkeley Laboratory.

For all simulation cases exterior temperature is taken as 0*°C* and interior space temperature is taken as 20*°C*. In order to calculate linear thermal transmittance heat flow per meter celcius degree is derived.

Besides, heating system is modelled as conventional heating which works based on natural gas and cooling system is modelled as split air conditioner.

4.7.1 Assessment of building energy performance for Case-1

This chapter explains how builidng energy performance is simulated based on Therm outputs for case-1.

4.7.1.1 Results of 2-D heat flow simulations

This section describes the results of Therm 7.3 simulations.

Following figures illustrates isothermal, color infrared and heat flux magnitude simulation results for Case-1.

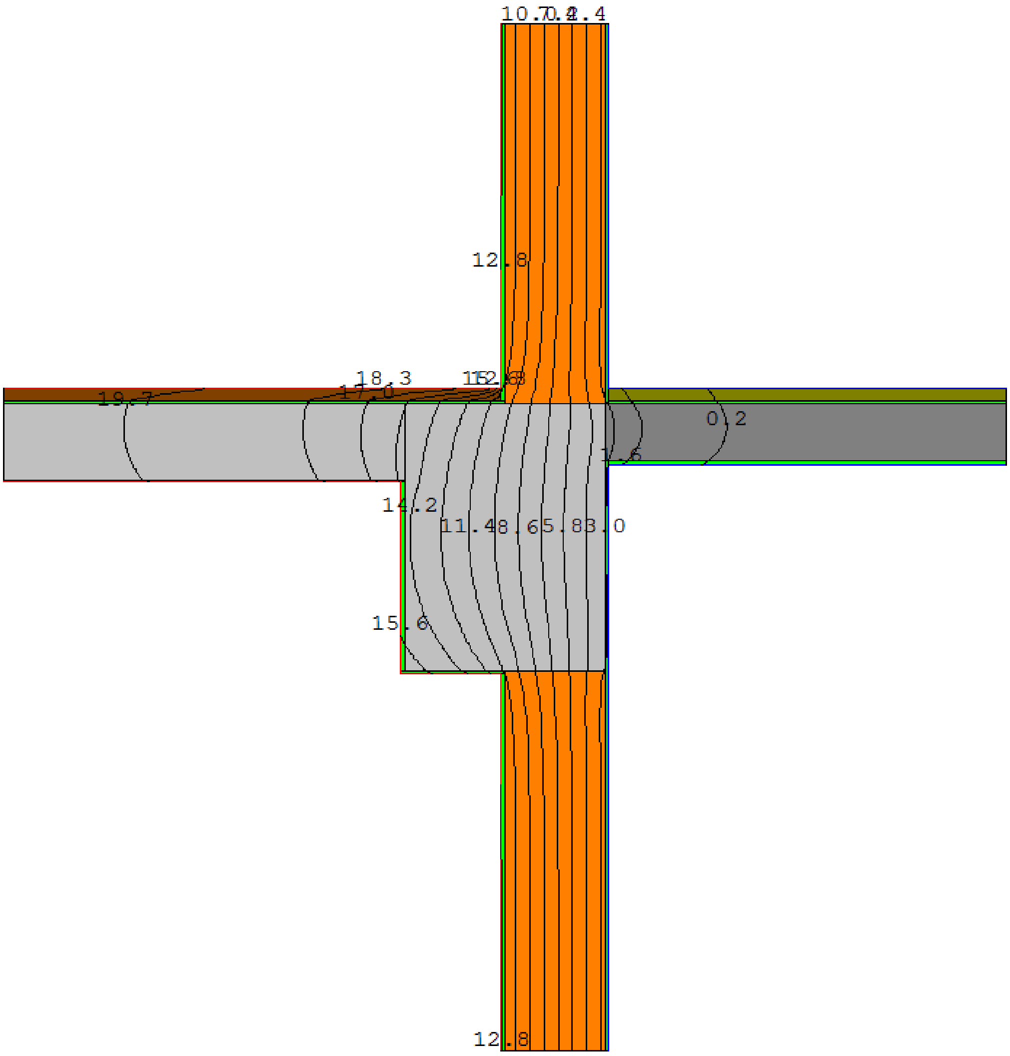


Figure 4.17 : Isothermal graph of case-1.

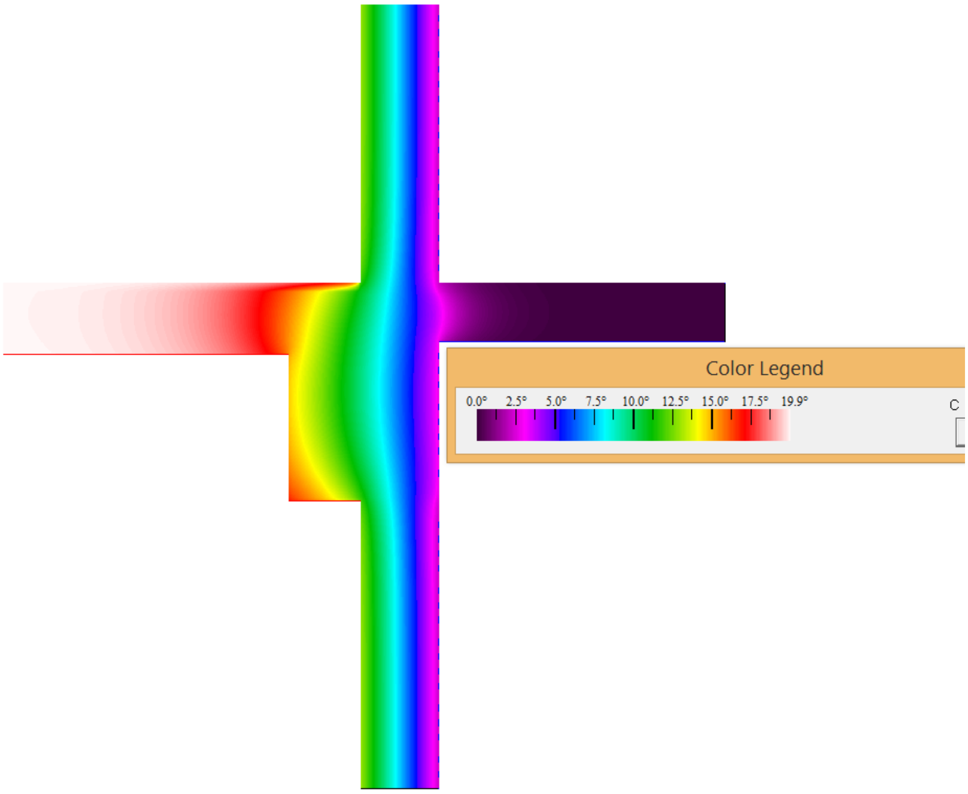


Figure 4.18 : Color infrared graph of case-1.

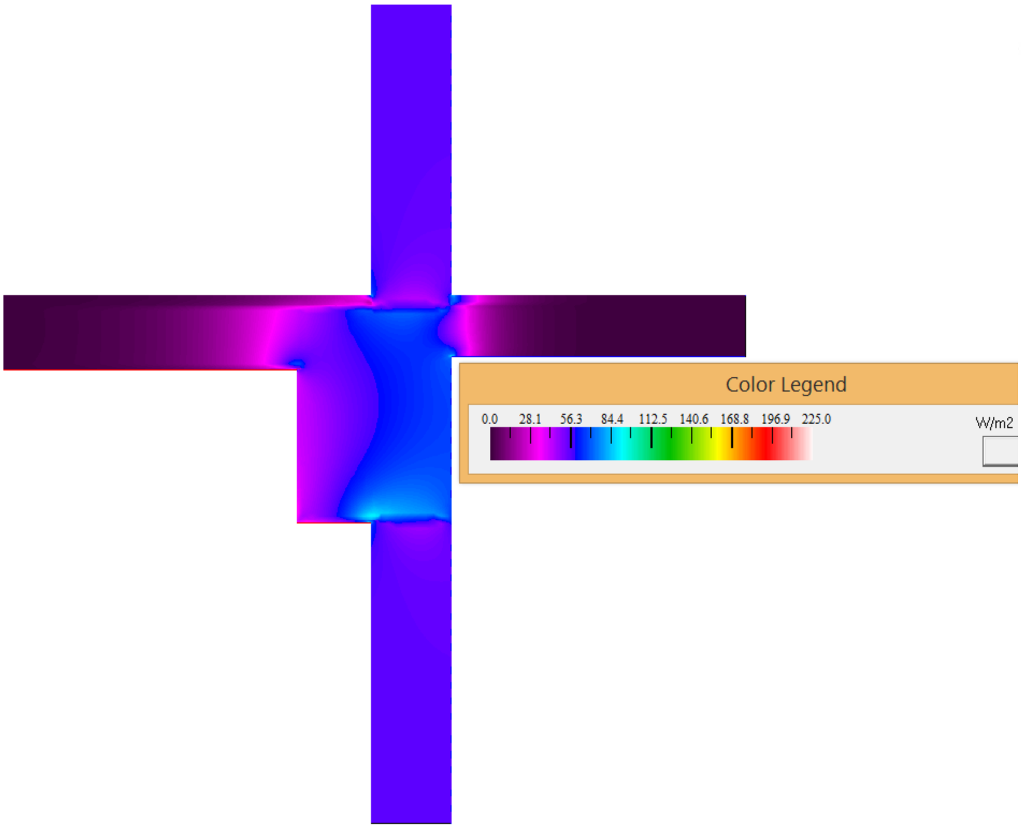


Figure 4.19 : Heat flux magnitude of case-1.

As it can be seen from the figure 4.17, a fluctuation is detected on balcony slab, indoor floor and beam. This situation can be called as a thermal bridge.

As shown in the figure 4.18, temperature of indoor floor decreases from left hand side to balcony corner. High thermal conductivity of reinforced concrete and low reinforce concrete is caused to temperature decrease on internal floor.

As demonstrated in the figure 4.19, heat flux rate on beam and balcony slab is higher than walls. Because of high thermal conductivity of balcony slab.

Results of building energy performance analysis for Case-1

In order to evaluate building energy performance, overall U values are calculated on the basis of linear thermal transmittance and inputted into the model which developed by using eQuest software.

According to building energy performance simulation heating energy consumption is calculated as 108134.58 *kWh*, cooling energy consumption is calculated as 11600 kWh and total energy consumption is calculated as 151937.04 *kWh* for case-1.

Following bar chart illustrates the heating, cooling and total energy consumption for Case-1.

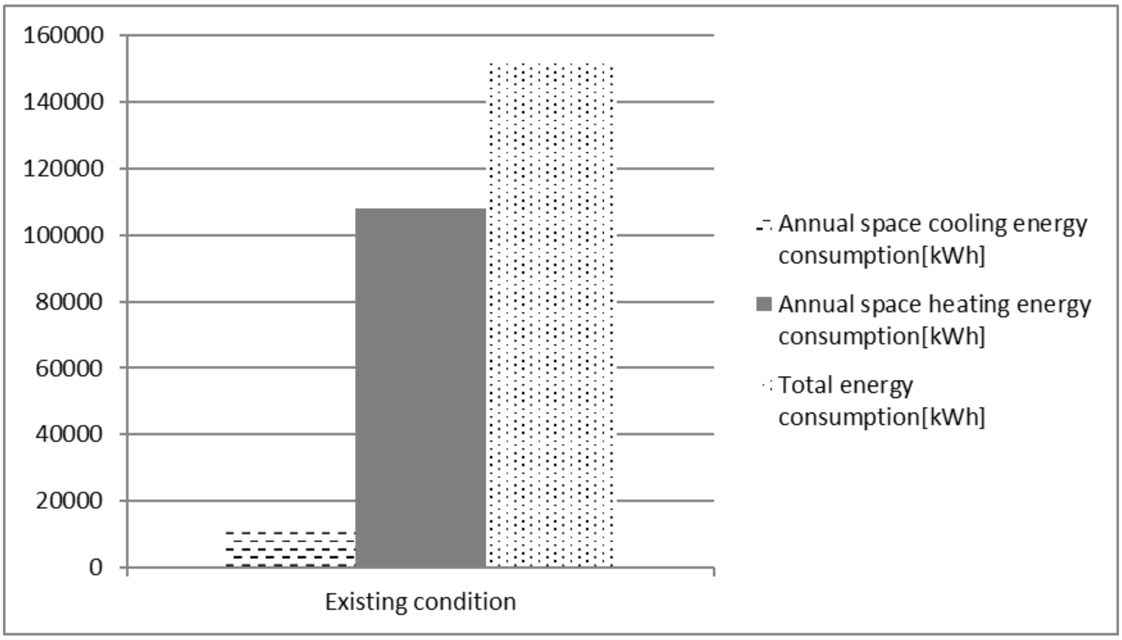


Figure 4.20: Annual energy consumption values of case-1.

Calculation results of floor surface temperature

Following line chart presents floor temperature distribution from balcony corner.

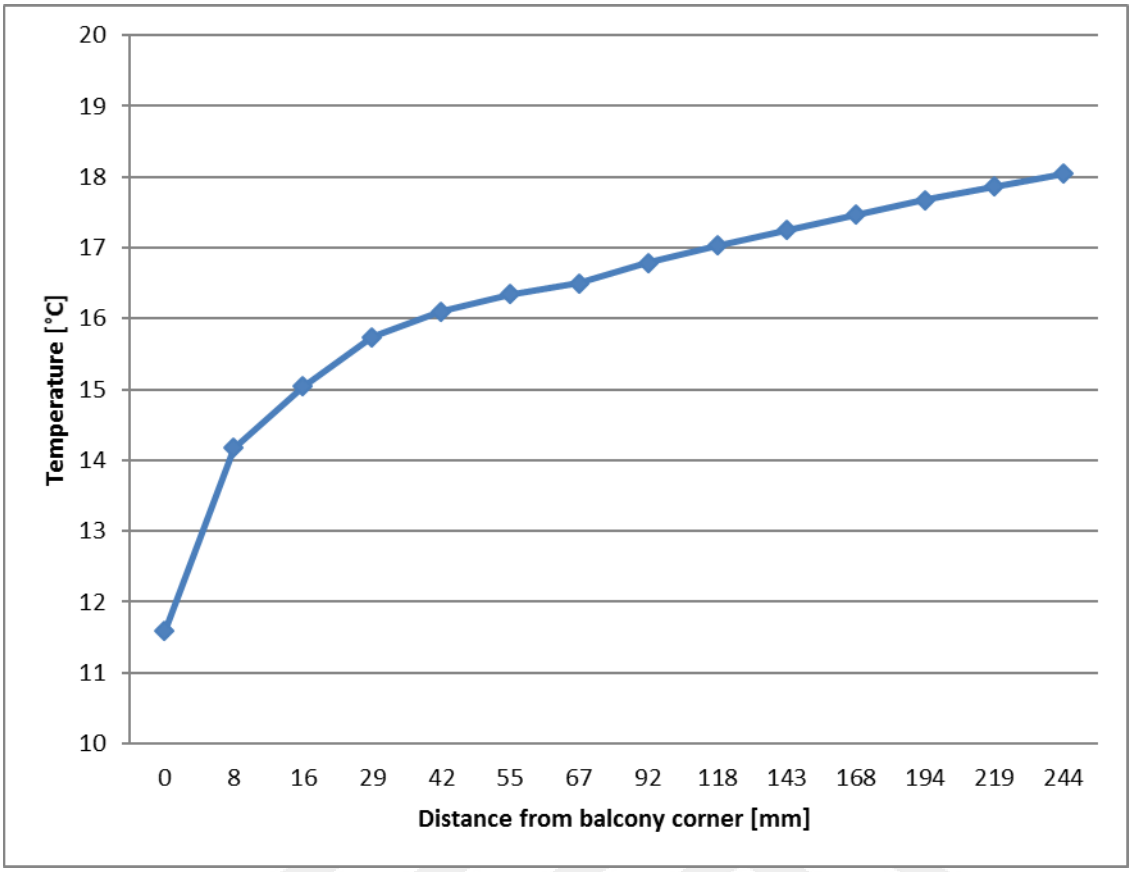


Figure 4.21 : Surface temperature distribution as a functuon of distance from balcony corner for case-1.

As it can be seen in the line chart, Indoor corner temperature is approximately 11 *°C*. In order to evaluate condensation risk on the surface, surface temperature factor is calculated in section 4.6.

The calculation result of surface temperature factor yielded 0.579. As mentioned in previous chapters, the minimum value of surface temperature factor for dwellings is suggested as 0.75.

Consequently, Case-1 has condensation potential on internal surface.

4.7.2 Assessment of building energy performance for Case-2

This chapter explains the evaluation of building energy performance based on Therm and Equest results for case-2.

4.7.2.1 Results of 2-D heat flow simulations

Following figures illustrates isothermal, color infrared and heat flux magnitude simulation results for Case-2.

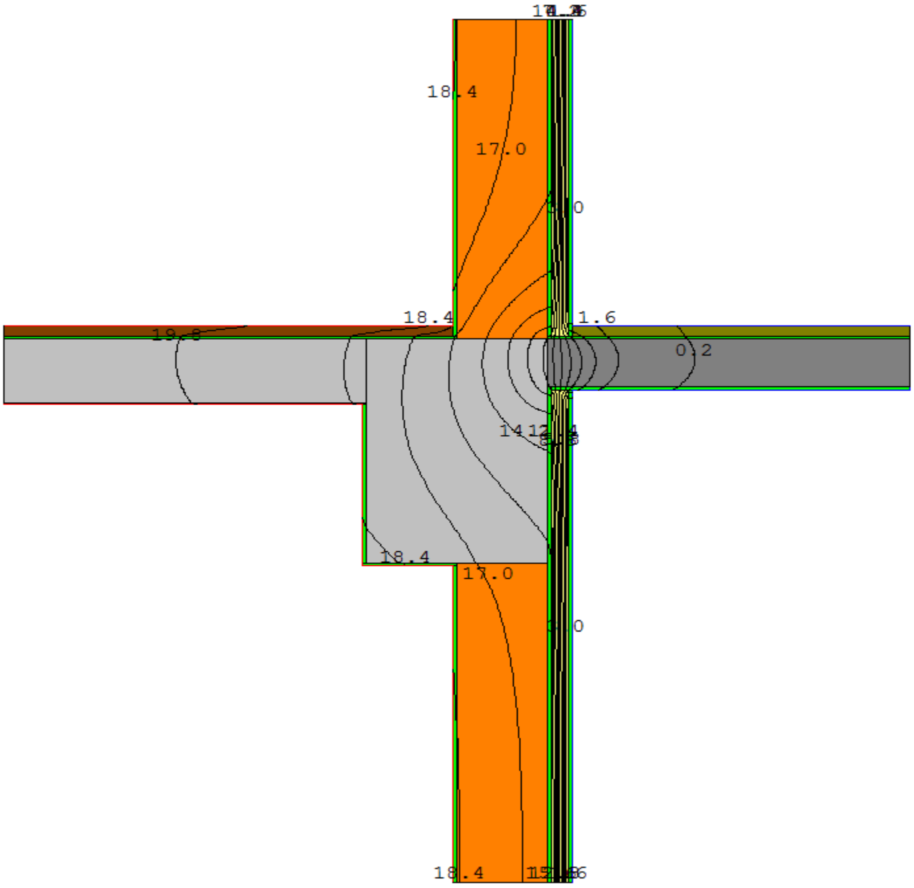


Figure 4.22 : Isothermal graph of case-2.

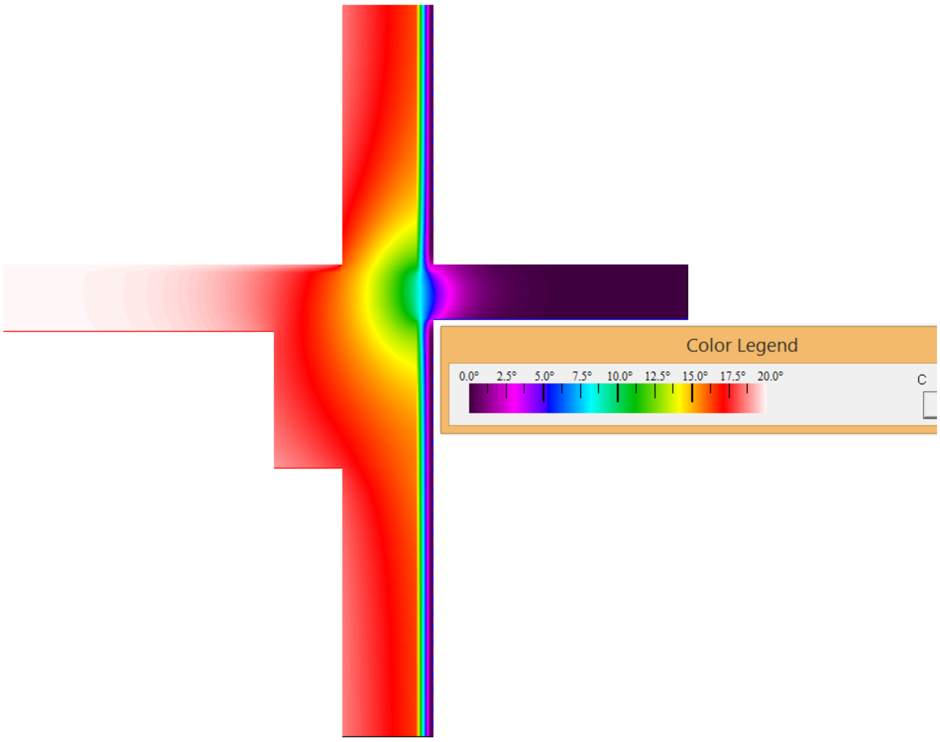


Figure 4.23 : Color infrared graph of case -2.

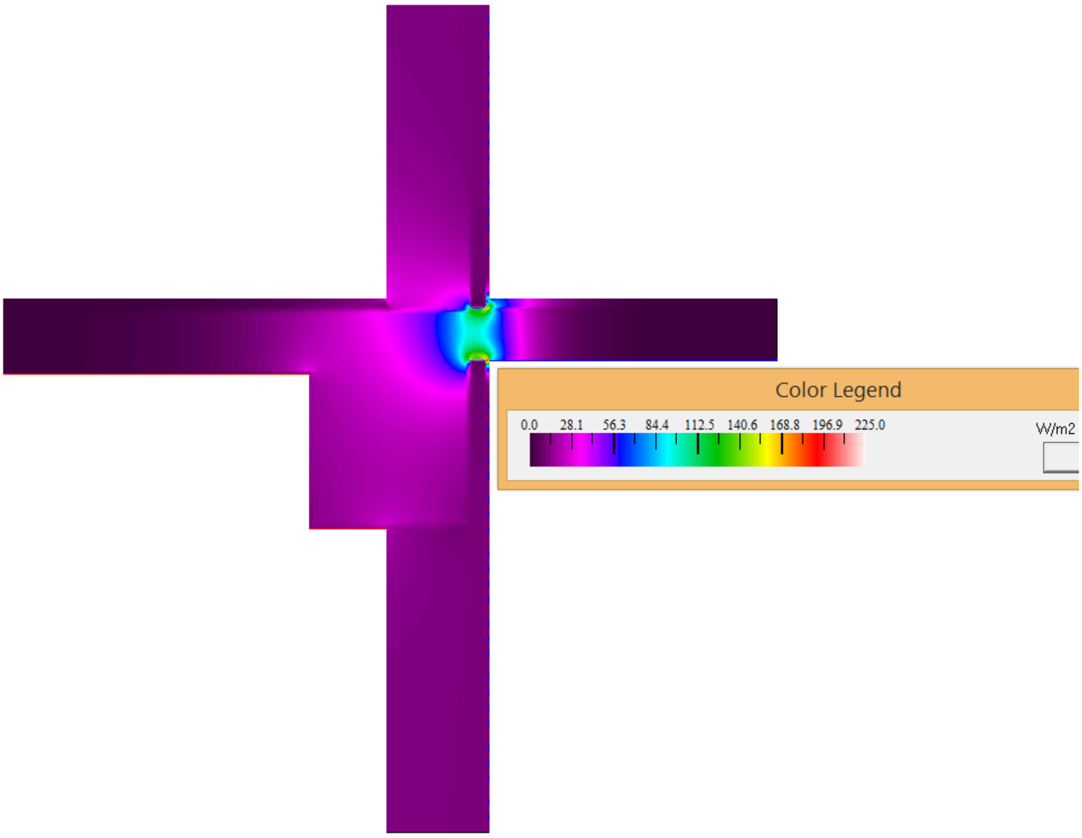


Figure 4.24 : Heat flux magnitude graph of case-2.

As shown in the figure 4.22, a sharp fluctuation on isothermal lines occurred on balcony slab. A possible explanation for this fluctuation might be that, instability of insulation material.

As it can be noticed from the figure 4.23, temperature decreases sharply from balcony slab to indoor floor. It seems possible that these result is due to high thermal conductivity of reinforced concrete, low reinforced concrete and instability of insulation material. An excessive heat loss takes place on balcony slab.

As mentioned in figure 4.24, heat flux takes place mostly on the floor due to instability of insulation material.

Results of building energy performance analysis for Case-2

In order to assess building energy performance, overall U values which obtained from linear thermal transmittance value inputted into the eQuest software.

According to building energy performance simulation heating energy consumption is calculated as 55324.26 *kWh*, cooling energy consumption is calculated as 9010 *kWh* and total energy consumption is calculated as 90953.79 *kWh* for case-2.

Following bar chart illustrates heating, cooling and total energy consumption of the building for case-2.

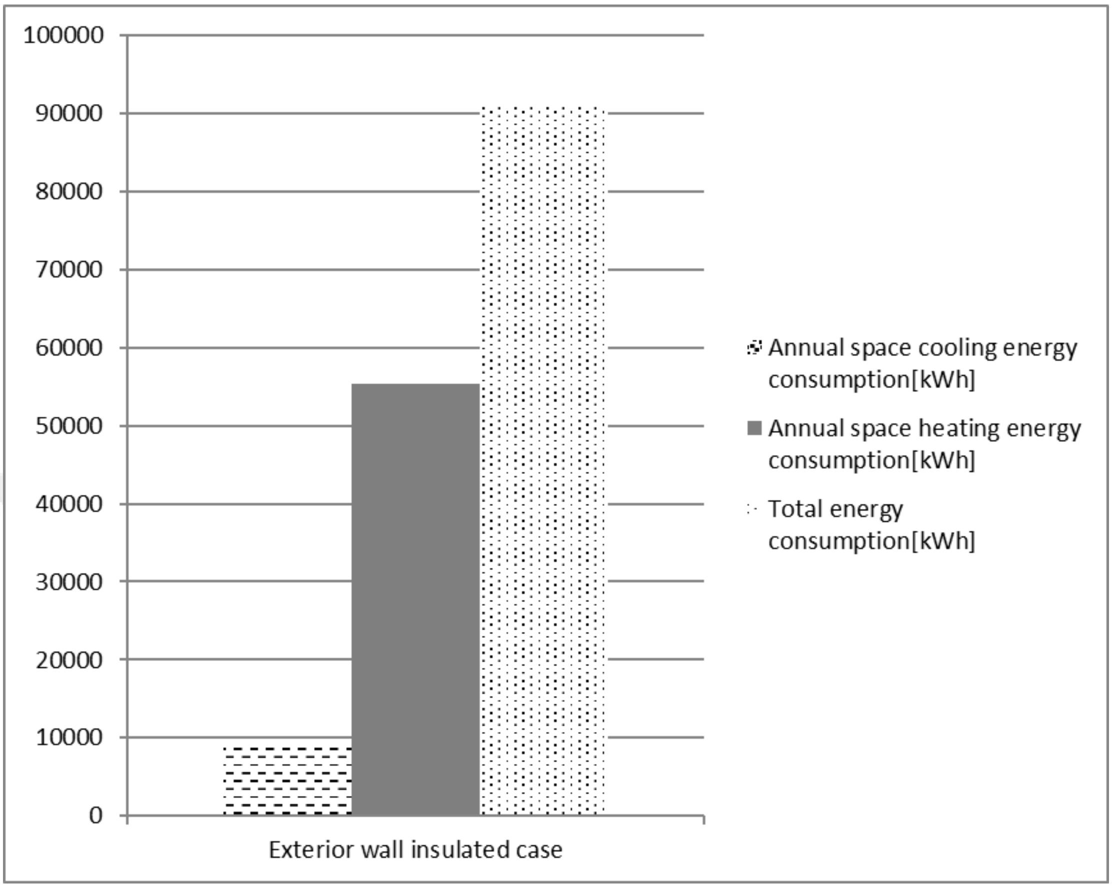


Figure 4.25 : Annual energy consumption values for case-2.

Calculation results of floor surface temperature

As described in previous chapters surface temperature factor is an indicator for surface condensation. In order to investigate surface condensation a detailed calculation must be performed. However, in this study surface condensation potential is evaluated using surface temperature factor. Besides, surface condensation potential directly effects indoor air quality.

In order to evaluate surface condensation potential risk, surface temperature factor is calculated for case-2 in section 4.6.

As mentioned in previous sections, suggested minimum value for surface condensation potential is 0.75. However, in our case it is calculated as 0.806. this means that Case-2 has no surface condensation potential for floor.

Following line chart presents indoor floor temperature from balcony corner.

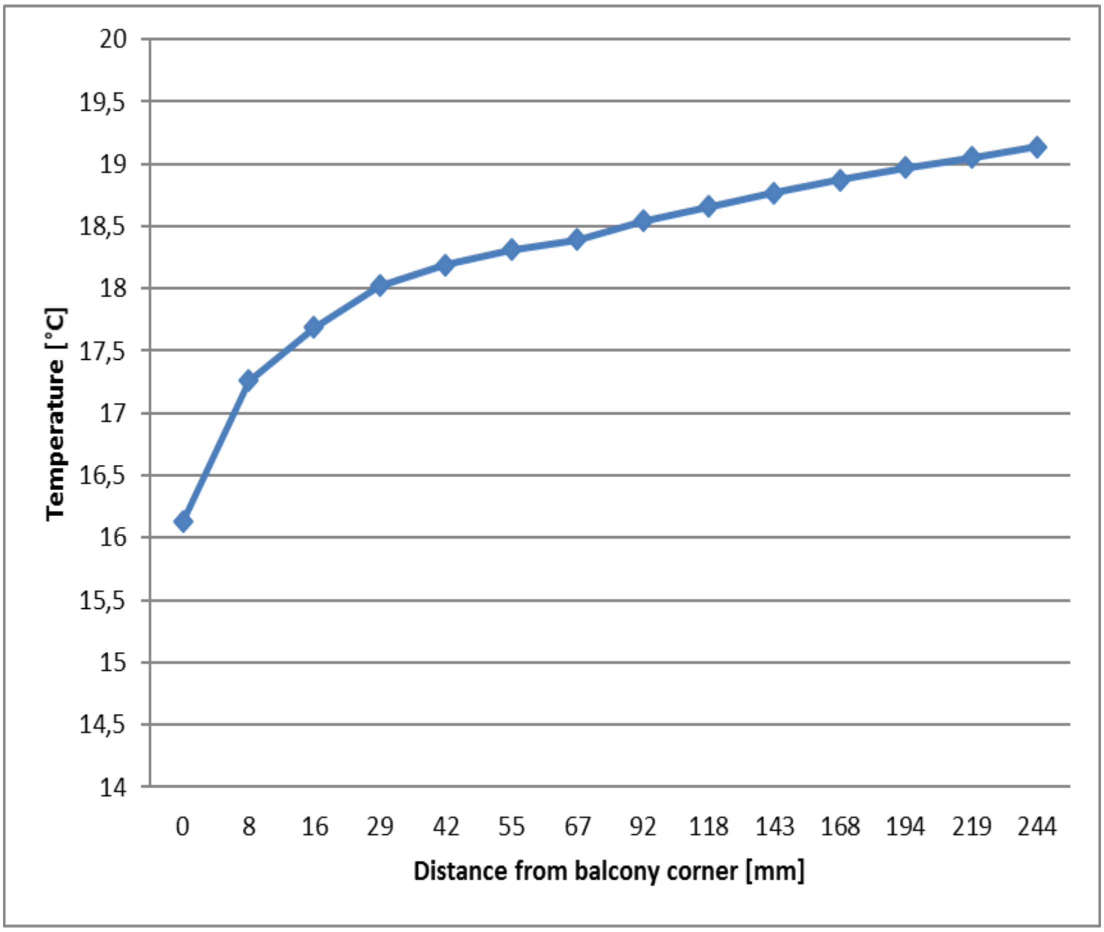


Figure 4.26 : Floor surface temperature distribution as a function of distance from balcony corner of case-2.

As it can be noticed on the line chart, minimum temperature detected on the corner of the balcony slab as approximately $16°C$.

4.7.3 Assessment of building energy performance for Case-3

This chapter explains building energy performance assessment based on Therm and Equest results for case-3.

4.7.3.1 Results of 2-D heat flow simulations

Following isotherm, color infrared and heat flux magnitude graphs illustrate temperature distribution of the model for Case-3

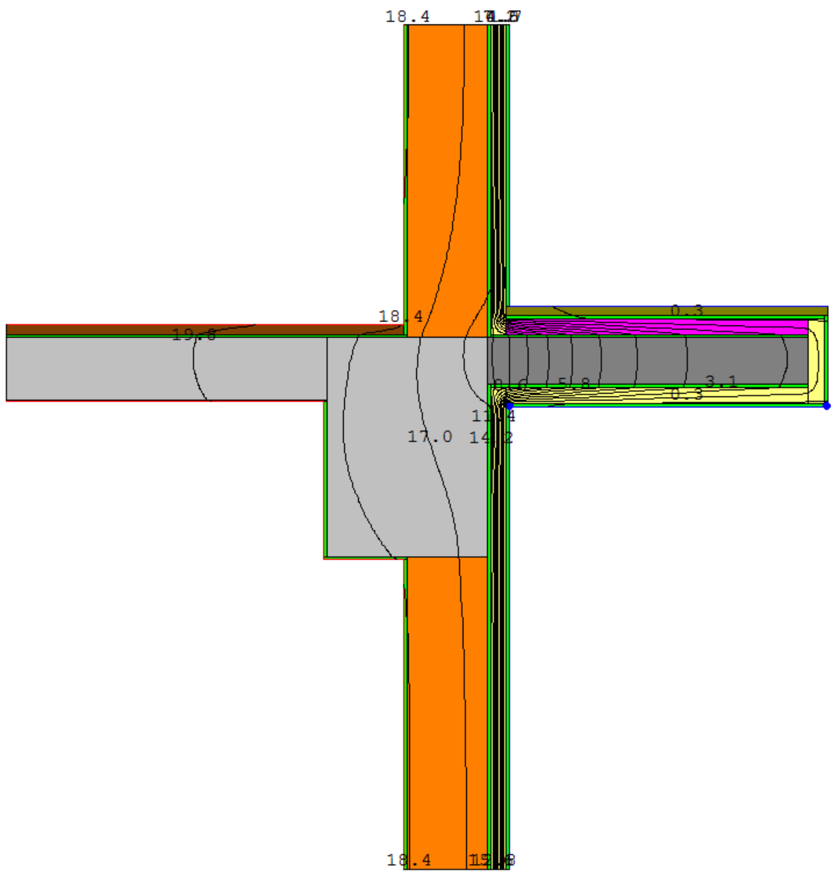


Figure 4.27 : Isothermal graph of case-3.

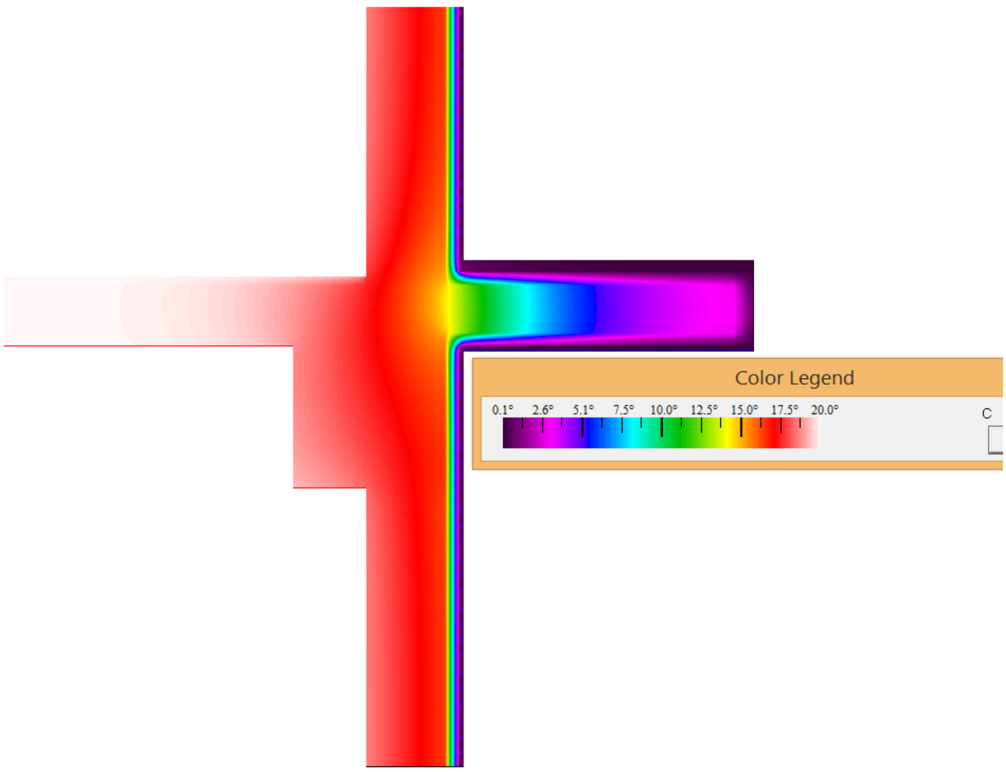


Figure 4.28 : Color infrared graph of case-3.

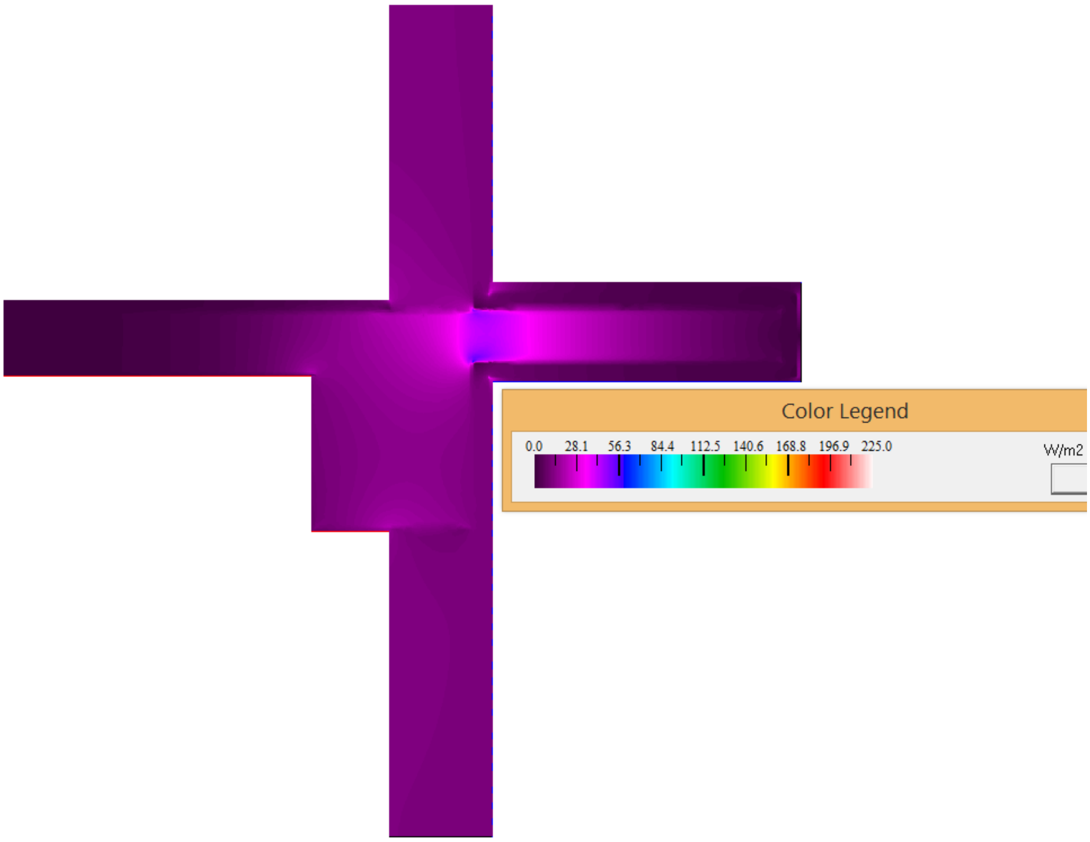


Figure 4.29 : Color infrared graph of case-3.

As demonstated in the figure 4.27, temperature of balcony slab and internal floor id increased.

As shown in the figure 4.28, temperature of indoor floor and balcony slab is increased.

As it can be seen from the figure 4.29, heat flux is decreased because of the effective insulation of thermal bridge.

Results of building energy performance analysis for Case-3

In order to evaluate heating, cooling and total energy consumption, new psi value is calculated for insulated balcony slab and overall U value is derived on the basis of Therm 7.3 outputs. Overall U values are inputted into the eQuest software to calculate building energy performance.

According to building energy performance simulation heating energy consumption is calculated as 52886.5 *kWh*, cooling energy consumption is calculated as 8910 *kWh* and total energy consumption is calculated as 88156.03 *kWh* for case-3.

Following bar chart shows heating, cooling and total energy consumption of building for Case -3.

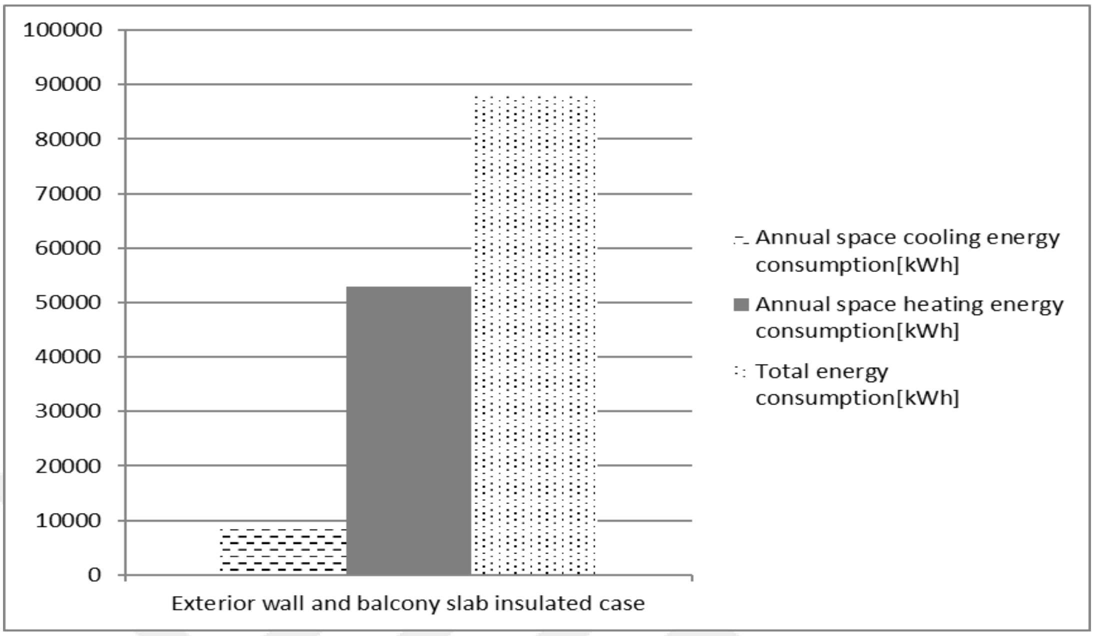


Figure 4.30 : Annual energy consumption values for case-3.

Calculation results of floor surface temperature

Following line chart shows indoor floor temperature from balcony corner as a function of distance from balcony corner.

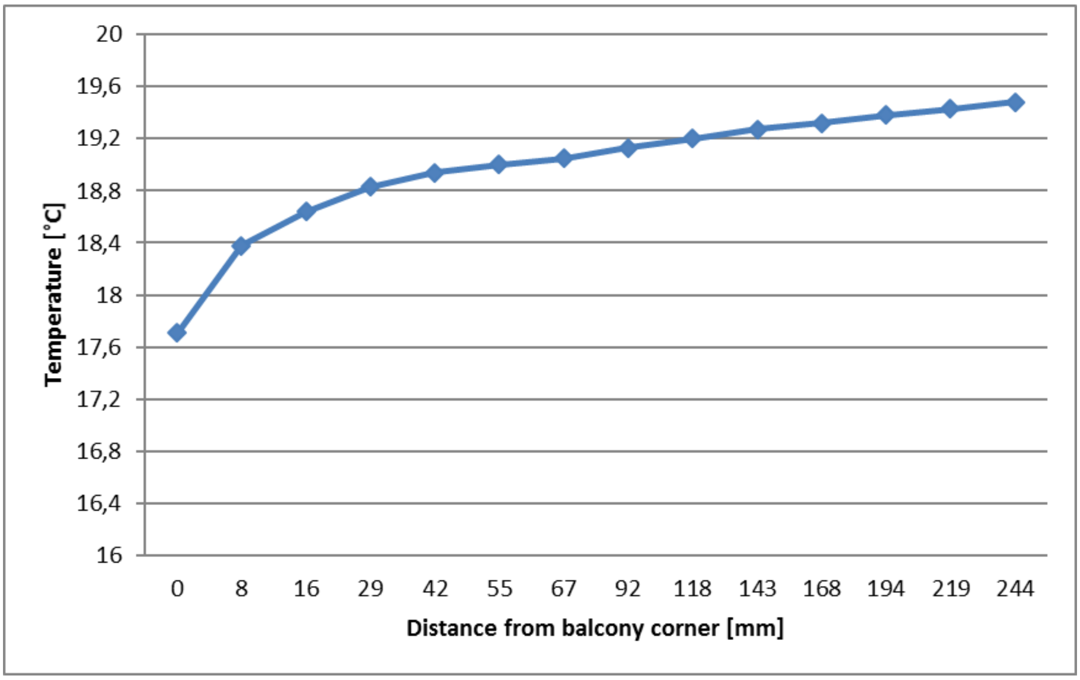


Figure 4.31 : Floor surface temperature values as a function of distance from balcony corner for case-3.

In the line chart, minimum value of corner approximately 17$°C$. In order to evaluate surface condensation potential surface temperature factor is calculated in section 4.6 as 0.885.

Because of 0.885 is higher than 0.75 our case has no condensation risk on balcony corner.

5. CONCLUSION

This thesis, examined the relationship between balcony thermal bridge and building energy performance for Turkish climate conditions. Three case study is developed as listed below;

Case-1: Existing condition (uninsulated);

Case-2: Exterior wall insulated condition;

Case-3: Exterior wall and balcony slab insulated condition.

simulations are performed for each case study and results are listed in previous chapters.

This chapter evaluates comparative results of each case in terms of heating, cooling and total energy consumption. Besides, percentage decrease or percentage increase in building energy consumptions are assessed. Moreover, indoor floor surface temperatures are compared between each three cases.

Following line chart illustrates heat flow rate per meter for each three cases.

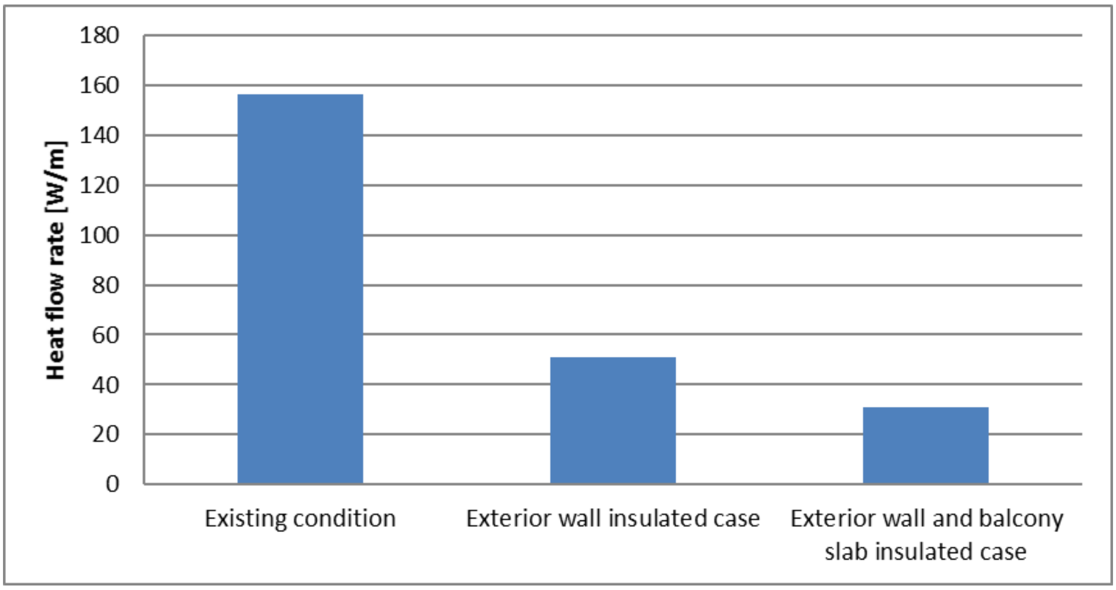


Figure 5.1 : Graph of heat flow rate for three cases.

As it can be seen from the chart, heat flow rates decrease by addition of insulation layer to exterior wall and balcony slab. These values are used to calculate linear thermal transmittance to obtain overall U values.

Following line chart presents calculated linear thermal transmittance values for each three cases. These values are calculated based upon Therm7.3 software outputs and derived to overall U value as mentioned above.

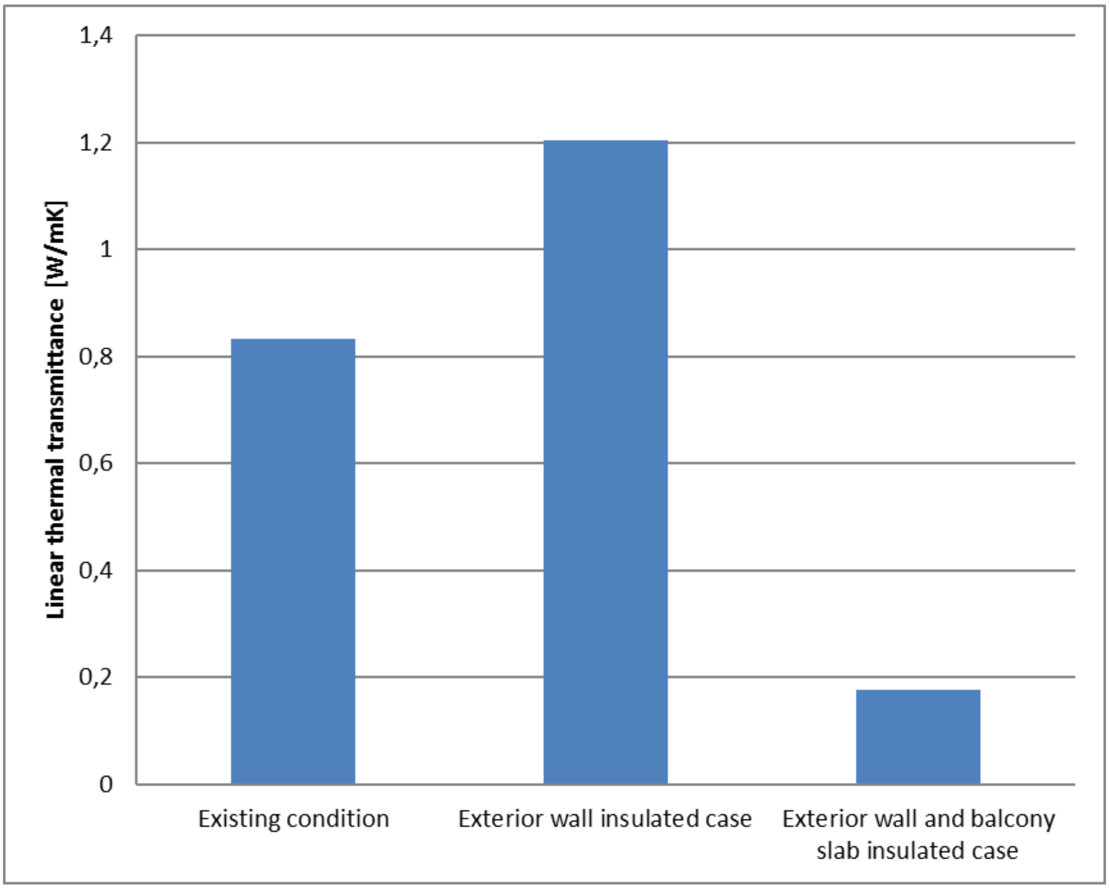


Figure 5.2 : Graph of linear thermal transmittance for three cases.

From the chart it can be seen that, linear thermal transmittance increases with addition of insulation layer to the wall (Exterior wall insulated case). Interestingly, this increase is related to heat flow through balcony slab. Heat flow is similar with electric current. Addition of insulation is decreased thermal conductivity of wall also contrast between extwrior wall and balcony slab is increased in terms of thermal conductivity. Thus, linear thermal transmittance of selected surface is increased.

Following line chart illustrates calculated U values on the basis of linear thermal transmittance values.

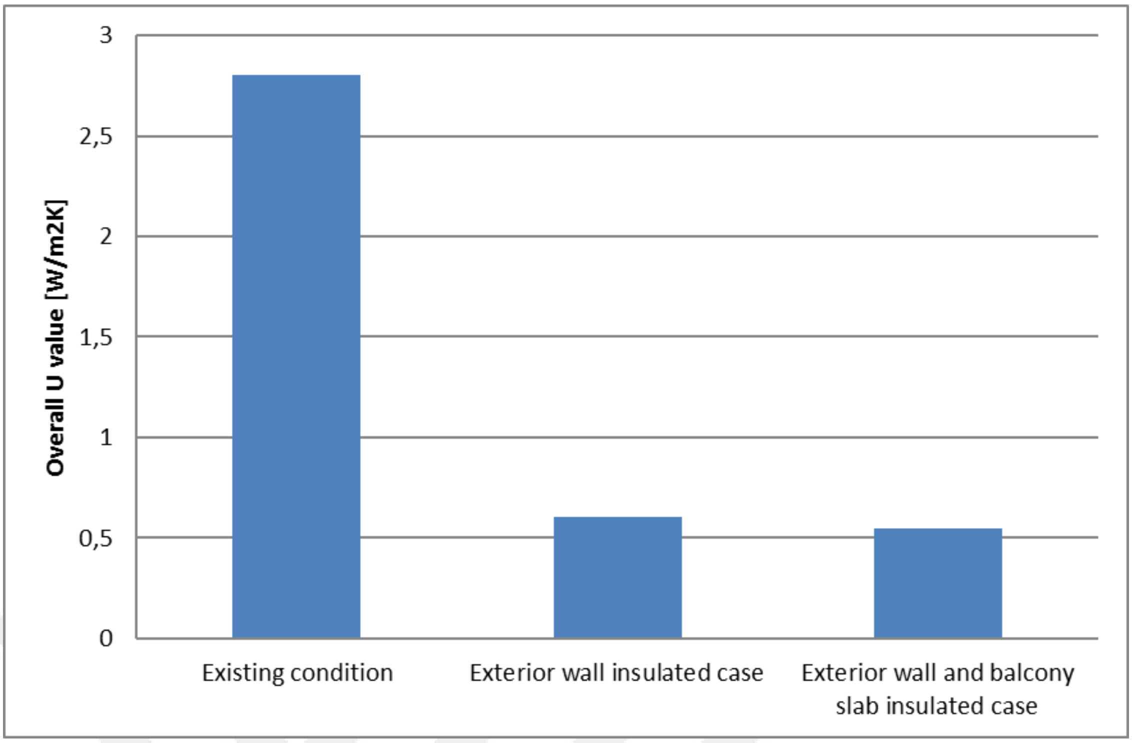


Figure 5.3 : Graph of overall U value for three cases.

As it can be seen in the graph above, case-1 has the highest overall U value. However, case-1 does not have the highest linear thermal transmittance value as illustrated before overall U value chart.

These relationships may partly be explained by decrease in exterior wall U value with the insulation.

Following table shows energy consumption of building in terms of heating, cooling, and total energy. Furthermore, percentage change in consumptions are presented as well.

Table 5.1 : Annual energy consumption values for each three cases.

	Heating energy consumption [*kWh*]	Cooling energy consumption [*kWh*]	Total energy consumption [*kWh]*	% heating energy change	% cooling energy change	% total energy change
Case-1	108134.58	11600	151937.04	-	-	-
Case-2	55324.26	9010	90953.79	95.455	28.745	67.05
Case-3	52886.5	8910	88156.03	4.609	1.122	3.173

As, it can be seen in the table above, heating, cooling and total energy consumption decreases by inclusion of insulation material.

Following bar chart illustrates energy consumption values of building for each three case in terms of heating, cooling and total energy consumption.

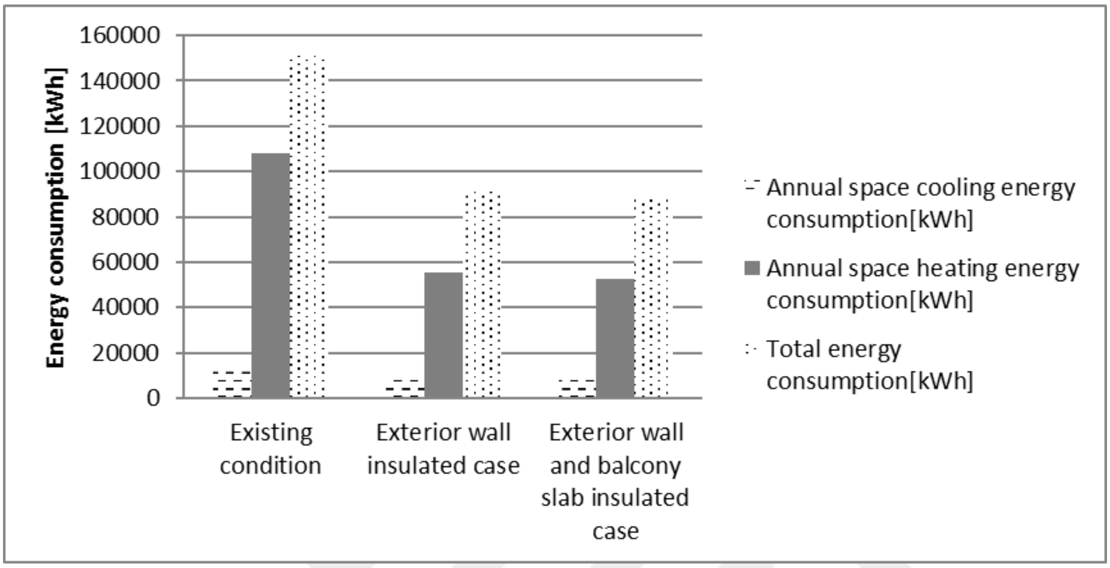


Figure 5.4: Annual energy consumption graphs of three cases.

As it can be ssen from the figure above, energy consumptions are decreased by addition of insulation layer to the building.

Following line chart presents heating energy consumption and percentage heating energy consumption decrease of building for each three cases.

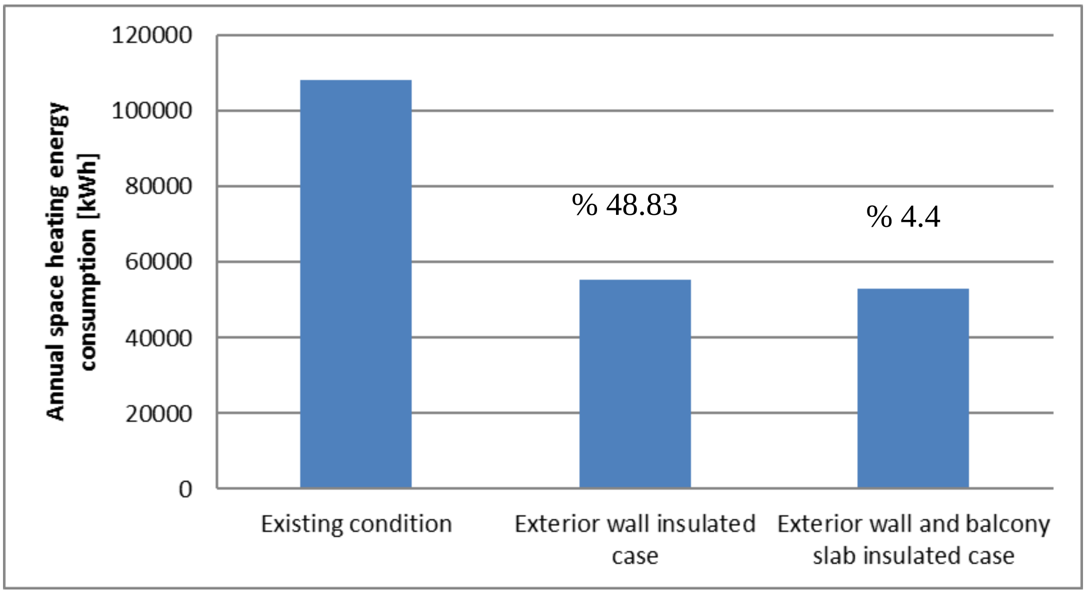


Figure 5.5 : Annual space heating energy consumption graph of thee cases.

As it can be seen from the line chart above, heating energy consumption is decreased by 48.8% with the addition of insulation layer to the exterior wall which is case-2. Moreover, heating energy consumption is decreased by 4.4% with the insulation of exterior wall and balcony slab.

Following line chart illustrates cooling energy consumption and percentage cooling energy consumption decreased of building for each three cases.

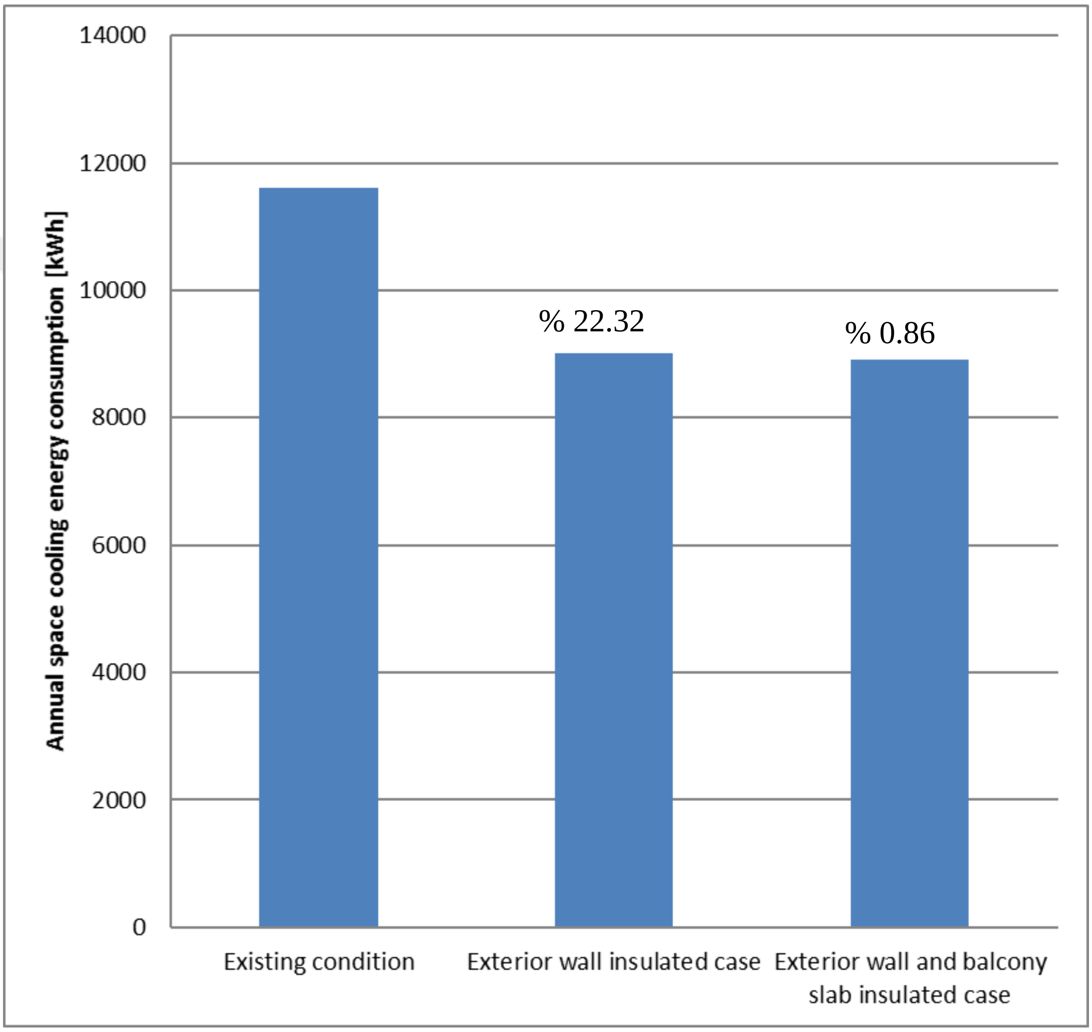


Figure 5.6 : Annual space cooling energy consumption graph of three cases.

As it can be seen from the line chart above, cooling energy consumption is decreased by 22.3% with the addition of insulation layer to the exterior wall which is case-2. Moreover, heating energy consumption is decreased by 0.8% with the insulation of exterior wall and balcony slab.

Following line chart shows total energy consumption and percentage total energy consumption decrease of building for each three cases.

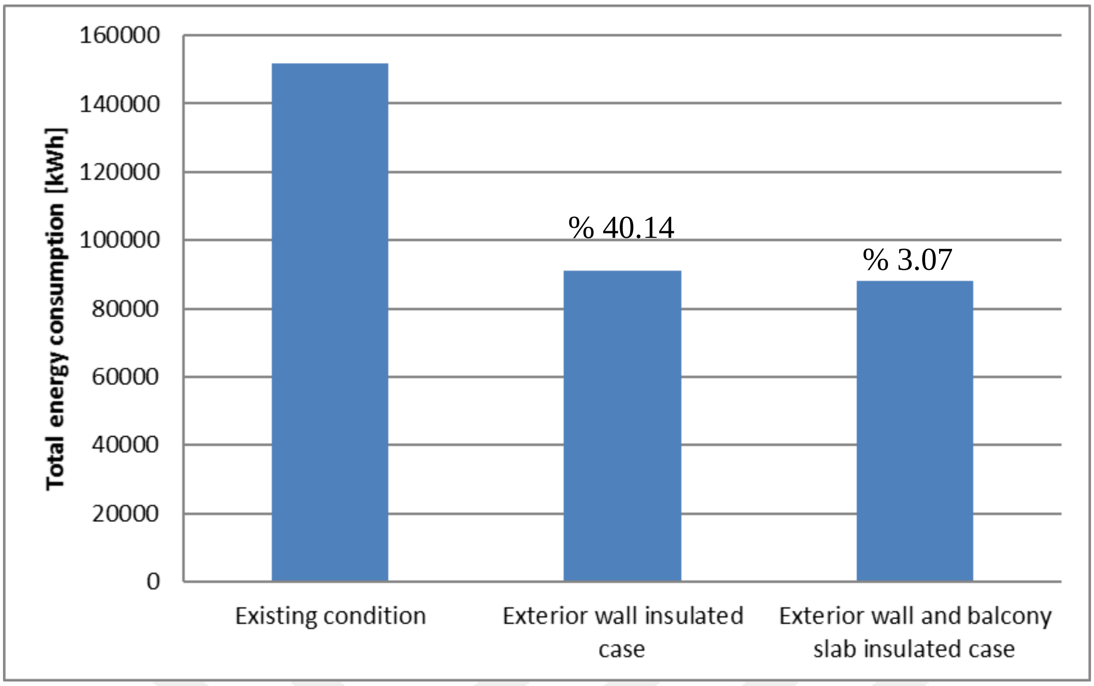


Figure 5.7 : Annual total energy consumption graph of three cases.

As it can be seen from the line chart above, total energy consumption of the building is decreased by 40.1% with the addition of insulation layer to the exterior wall which is case-2. Moreover, total energy consumption of the building consumption is decreased by 3.07% with the insulation of exterior wall and balcony slab.

Following line chart presents indoor floor surface temperatures of building as a function of distance from balcony corner.

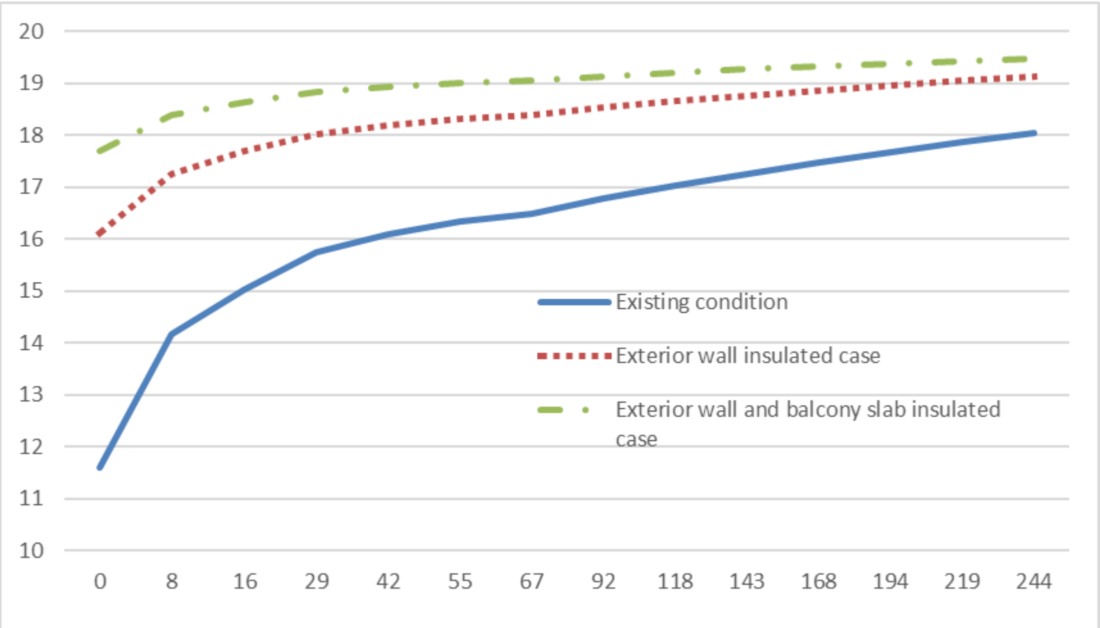


Figure 5.8 : Floor surface temperature distribution graph of three cases.

As it can be seen from the chart above, indoor floor temperatures increase sharply with insulation of exterior wall however, it increases slightly with insulation of the balcony slab. These results are likely to be related to total area of exterior wall is more than balcony cross section area.

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